EFFECTS OF EXTREMITY ARMOR ON METABOLIC COST AND GAIT BIOMECHANICS

Albert A. Adams III

A thesis to be submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Master of Science

Submitted by:

Albert A. Adams III
Department of Biomedical Engineering

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Approved by:

Kristen Billiar, PhD Associate Professor Department of Biomedical Engineering	Jeffrey Schiffman, PhD Research Biomechanist U.S. Army Natick Soldier RDEC
______________________________	______________________________
Glenn Gaudette, PhD Assistant Professor Department of Biomedical Engineering	Leif Hasselquist, PhD Research Biomechanist U.S. Army Natick Soldier RDEC
______________________________	______________________________

May 26, 2010

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **26 MAY 2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Effects of Extremity Armor on Metabolic Cost and Gait Biomechanics**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Worcester Polytechnic Institute ,100 Institute Road,Worcester,MA,01609-2280**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Modern ballistic armor can protect soldiers against gunfire and shrapnel. The added weight and movement restriction of armor on the extremities may negatively impact a soldier?s performance. Loading the limbs with weight has been found to increase metabolic cost in locomotion and alter gait kinematics. It was hypothesized that increases in metabolic cost and alterations in gait kinematics would result from the use of extremity armor. Fifteen healthy U.S. Army men walked (1.34 m/s) and ran (2.46 m/s) on a level treadmill with three different levels of extremity armor configuration: a no armor condition (4.3 lbs) that consisted of minimal clothing, combat boots, and a helmet; a partial extremity armor configuration (27.2 lbs) that consisted of an armor vest and extremity armor on the upper arms and thighs plus the minimal clothing; and a full extremity armor configuration (29.2 lbs) that consisted of forearm and shank armor in addition to the partial extremity armor configuration. In walking and running on the treadmill, metabolic cost normalized to body mass increased significantly when extremity armor was worn, as compared to the no armor condition. No difference was found in metabolic cost scaled to total mass (body mass + mass of armor), indicating no effect of mass placement. When walking on the treadmill, double support time was the only temporal variable found to increase with use of extremity armor; no differences between partial and full armor configurations were found. Range of motion (ROM) of the ankle decreased in walking with extremity armor, while hip and knee ROMs increased with the use of extremity armor. In running, only hip ROM and trunk lean increased significantly with the use of extremity armor, while no difference was found between the two extremity armor configurations. In conclusion, use of extremity armor on soldiers walking and running on a level treadmill resulted in a metabolic cost increase as the mass of the armor increased and did affect gait kinematics. The distal placement of the armor on the extremities at the low mass tested did not significantly affect metabolic cost or gait kinematics.

15. SUBJECT TERMS

<table>
<tr><td colspan="3">16. SECURITY CLASSIFICATION OF:</td><td rowspan="2">17. LIMITATION OF ABSTRACT
Same as Report (SAR)</td><td rowspan="2">18. NUMBER OF PAGES
109</td><td rowspan="2">19a. NAME OF RESPONSIBLE PERSON</td></tr>
<tr><td>a. REPORT
unclassified</td><td>b. ABSTRACT
unclassified</td><td>c. THIS PAGE
unclassified</td></tr>
</table>

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

ACKNOWLEDGEMENTS

I would like to thank my advisors, Jeff Schiffman, Leif Hasselquist, Kristen Billiar, and Glenn Gaudette, for guiding me throughout the process of working on this thesis, from the development of a thesis topic to the final revisions. Their constant availability for questions and willingness to review my work even during weekends and vacation was greatly appreciated. I would also like to recognize the efforts of Karen Gregorczyk, Carolyn Bensel, Megan Coyne, Bob Mello, and Joe Seay, who collected the data that was analyzed in this study, and were willing to share their insight whenever it was needed. Lastly, I should acknowledge the U.S. Army for funding this project.

ABSTRACT

Modern ballistic armor can protect soldiers against gunfire and shrapnel. The added weight and movement restriction of armor on the extremities may negatively impact a soldier's performance. Loading the limbs with weight has been found to increase metabolic cost in locomotion and alter gait kinematics. It was hypothesized that increases in metabolic cost and alterations in gait kinematics would result from the use of extremity armor. Fifteen healthy U.S. Army men walked (1.34 m/s) and ran (2.46 m/s) on a level treadmill with three different levels of extremity armor configuration: a no armor condition (4.3 lbs) that consisted of minimal clothing, combat boots, and a helmet; a partial extremity armor configuration (27.2 lbs) that consisted of an armor vest and extremity armor on the upper arms and thighs plus the minimal clothing; and a full extremity armor configuration (29.2 lbs) that consisted of forearm and shank armor in addition to the partial extremity armor configuration. In walking and running on the treadmill, metabolic cost normalized to body mass increased significantly when extremity armor was worn, as compared to the no armor condition. No difference was found in metabolic cost scaled to total mass (body mass + mass of armor), indicating no effect of mass placement. When walking on the treadmill, double support time was the only temporal variable found to increase with use of extremity armor; no differences between partial and full armor configurations were found. Range of motion (ROM) of the ankle decreased in walking with extremity armor, while hip and knee ROMs increased with the use of extremity armor. In running, only hip ROM and trunk lean increased significantly with the use of extremity armor, while no difference was found between the two extremity armor configurations. In conclusion, use of extremity armor on soldiers walking and running on a level treadmill resulted in a metabolic cost increase as the mass of the armor increased and did affect gait kinematics. The distal placement of the armor on the extremities at the low mass tested did not significantly affect metabolic cost or gait kinematics.

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CHAPTER 1: INTRODUCTION

Protecting soldiers is the number-one priority of the U.S. Army (Interceptor Body Armor (IBA), 2009). Due to the nature of the asymmetric warfare currently being confronted on the modern battlefield, a highly mobile, agile ground force that can contend with constantly evolving threats in diverse environments is required. While modern ballistic protection equipment can greatly help to protect against many of the threats being faced, the added weight and movement restriction of such armor can also become a hindrance on the battlefield, putting soldiers in greater danger. In order to optimize the warfighter, the balance between ballistic protection and functionality must be found, with each trade-off characterized so that commanders can make informed decisions on how to best equip their troops.

A majority of casualties from modern wars are the result of gunfire, explosions, and shrapnel (Owens et al., 2008). Over the last century, the U.S. military has devoted extensive resources to increasing the survivability of warfighters facing these threats. Advancements in ballistic protection in recent years have improved the level of protection while also reducing weight. Soldiers and Marines currently deployed to Iraq and Afghanistan are issued Interceptor Body Armor (IBA) vests, which protect against gunfire and shrapnel. The increased use of armor vests, as well as the improved protection they offer, has saved countless lives on the current battlefields, reducing the frequency and severity of injuries to the abdomen and chest (Peleg et al., 2006; Owens et al., 2008). Armor vests, however, can only offer protection to the thorax. While the occurrence of thoracic injuries has been significantly reduced by armor vests, damage to the arms and legs continue to account for a majority of casualties in Iraq and Afghanistan (Owens et al., 2008).

While applying ballistic armor protection to the extremities may reduce the frequency and severity of extremity injuries, as it has done for the torso, adding weight and material to the limbs has consequences that cannot be overlooked (Smith & Martin, 2007; Claremont & Hall,

1988; Martin, 1985). Increasing the load a soldier must carry or restricting his movement may negatively impact his performance so much that it is not worth the protection of the additional armor. On today's battlefield, missions may require long distance marches at high altitudes, during which any additional weight can increase fatigue and deplete morale (Knapik et al., 1991). While only anecdotal evidence is available from experiences in theater, laboratory testing has shown that increasing soldier loads results in reductions of performance in maneuvering through obstacle courses, hand grenade throwing, and completing a 20km road march (Holewijn & Lotens 1992; Knapik et al., 1997). Reducing the total load soldiers must carry has become such an important issue that the Army is currently experimenting, both in the laboratory and on the battlefield, with replacing the highly effective IBA vests with lighter ballistic armor vests, with less coverage area and less protection (Cox, 2009). In battle, a reduction in performance and maneuverability can become life threatening for the warfighter. Costs and benefits of additional armor for the extremities must be characterized prior to fielding such an armor system. While force protection is the number-one priority of the military, adding armor may not always be the best solution to reducing casualties. As one Army official has stated, "In some cases, mobility does equal survivability," (Stone, 2009).

Characterization of the biomechanical and physiological effects of new extremity armor systems on soldiers performing routine military tasks may be useful in demonstrating the costs of such systems. These effects could then be relayed to armor designers to help find the balance between protection and mobility for future systems. The information could simultaneously be supplied to commanders in the field so that they may make informed decisions on the use of each system of armor based on the needs of the mission, the protection offered by the armor, and the potential costs to a soldier's performance.

CHAPTER 2: BACKGROUND

While protecting soldiers with ballistic armor is not a new undertaking for the U.S. military, the application of ballistic armor to the arms and legs is novel. Currently, few studies have investigating the effects of extremity armor on soldier performance are publicly available. With a dearth of information on the effects of such extremity armor, researchers must draw on the existing base of knowledge on other forms of loading to the human body.

While walking and running do not account for all the ergonomic needs of the soldier, they are important facets of human performance. The dismounted ground troops, those soldiers for whom ballistic armor is designed, expend a majority of their energy on missions through walking and/or running. Therefore, one may want to begin an evaluation of a new armor system with characterizing its effects on locomotion. The purpose of this study is to characterize the physiological and kinematic costs of extremity armor in gait.

2.1 Ballistic Armor

While ballistic armor can protect against injury, it must reach the balance between protection and interference with mobility. If warfighters are unable to maneuver as needed for a mission due to cumbersome armor, they can become stationary targets. This may reduce their survivability, despite the added ballistic protection of the armor. Soldiers and Marines on the frontlines of battles are unlikely to accept armor that does not reach the appropriate balance between protection and mobility, rendering the armor unused.

The U.S. Army first began mass-issuing ballistic body armor to combat troops during the Korean War, but due to the low level of protection, defending against shrapnel but not gunfire, and movement infringing stiffness, the 8 pound M-1951 “flak vest” was not well received by troops. The M-1951 went largely unused, as warfighters felt that the level of protection it offered

did not make up for the weight and restriction of movement that it added. It was not until the development and incorporation of flexible Kevlar based ballistic protection in the 1980s that armor system gained acceptance with soldiers. This thinner, lighter, and more flexible vest, called the Personnel Armor System for Ground Troops (PASGT), marked a turning point, with ergonomic considerations playing a role in armor design. The PASGT offered improved protection, stopping shrapnel and handguns, while still allowing an acceptable level of flexibility and movement. Testing showed that the PASGT increased range of motion, ability to shoulder a rifle, and speed of execution of tasks over its predecessors (Bensel et al., 1980; Corona et al., 1974). Though the PASGT was comparable in weight to previous armor vests, study participants showed a preference for it over the predecessor, citing improved balance, comfort, and movement in the new PASGT vest. These tests proved that ergonomic design considerations, as well as improved protection, could make a difference in the adoption and use of ballistic armor.

The current generation of ballistic armor vest, the Interceptor Body Armor (IBA) vest was released in the late 1990s and uses a combination of a light weight, flexible Kevlar vest and ceramic plate inserts which increase ballistic protection. The ceramic inserts of the IBA vest increase the level of protection of the vest to the point where it can stop high velocity armor piercing rifle rounds. The modular IBA vest is considered to be extremely effective, stopping or slowing both bullets and shrapnel fragments to reduce the number and severity of thorax wounds (Interceptor Body Armor (IBA), 2009). Unlike previous armor systems, the IBA vest has also received tremendous acceptance from warfighters in the field, with over 80% of those questioned in Iraq stating that they felt the IBA vest did not interfere with the execution of mission related tasks (Greene, 2005). Since its initial release, multiple variants of the IBA vest have been designed and fielded, including the Outer Tactical Vest (OTV) and the Improved Outer Tactical Vest (IOTV) (**Figure 1**), each developed to meet the ergonomic needs of the warfighter.

Figure 1. Interceptor Body Armor (IBA) Vests. Outer Tactical Vest (OTV), on left, includes Kevlar vest with front and back ceramic plates. Improved Outer Tactical Vest (IOTV), on right, increases area of coverage over the OTV with more Kevlar and 2 additional ceramic plates on the sides of the vest.

Because of the high level of effectiveness, ergonomic design, and acceptance of the IBA vests, armor vests are now worn by Soldiers and Marines on every mission. This increase in use and protection of armor vests has played a significant role in the extraordinary increase in survival rates of Soldiers and Marines injured in Operation Enduring Freedom (OEF), in Afghanistan, and Operation Iraqi Freedom (OIF), in Iraq, as compared to previous conflicts (Mazurek & Ficke, 2006; Pollak, 2008). In World War II and Vietnam, only 69.7% and 76.4% of those warriors wounded in battle recovered from their injuries, respectively. In contrast, approximately 90% of American casualties injured in the current conflicts overseas have survived their wounds (Mazurek & Ficke, 2006; Pollak, 2008). While medical advancements and improvements in battlefield trauma care have certainly played a larger role in this increased survival rate, the contribution of bullet-resistant armor vests alone can be seen in the reduction of thoracic wounds among warfighters. The IBA has contributed to reduce the percentage of

casualties suffering from abdominal and chest trauma from 13% in the Vietnam War to about 6% in Iraq and Afghanistan (Owens et al., 2008; Scoville, 2004).

While the military has seen a reduction in torso wounds and an increase in the number of warfighters recovering from their injuries as a result of the armor vests, there have been an increased number of casualties being treated for extremity injuries (Hofmeister et al., 2007). Between October 2001 and January 2005, 82% of soldiers injured in OEF and OIF sustained extremity wounds, with injured soldiers averaging more than two extremity wounds each (Pollak, 2008). A 2003 survey of severely wounded Soldiers returning to the United States for treatment at the Walter Reed Army Medical Center specified that 60% of casualties were admitted with lower extremity injuries, while 30% had suffered upper extremity injuries (Montgomery et al., 2005). As of January 2009, the current military campaigns had resulted in over 3,575 American combatants being treated for extremity wounds, resulting in 1,286 military amputees (Fischer, 2009). These growing numbers are due to both the innovative enemies' use of improvised explosive devices, and the increased number of casualties surviving their injuries, as compared to previous conflicts. The improvements and increased use to armor vests have been successful, but such vests can only cover approximately 20 to 30% of the body's surface area (van de Linde & Lotens, 1988). The overwhelming number of serious injuries to the arms and legs clearly shows a need for protection of the extremities.

Past experience with armor vests, however, shows that new protection will not be accepted and used by soldiers based on the level of protection alone. Mobility and restriction of movement are equally important to soldiers with regards to body armor. While loading the torso with backpacks and/or body armor has been found to effect energy expenditure, ambulation biomechanics, and timed course performance, it has not been shown to affect soldiers' marksmanship, grenade throw accuracy, or cognitive ability (Knapik, 2001; Knapik et al., 1997; Quesada et al., 2000; Pandolf et al., 1977; Giovani & Goldman, 1971; Harman et al., 2000; Kramlich, 2005). Testing with the first generation of the IBA vest found that with wearing the

armor marksmanship was actually increased for short (50m) and intermediate (150m) distance targets, and only equal to accuracy without the vest for long (200m+) distance targets (Kramlich, 2005). Marches of 20km with 46kg loads, consisting of a backpack, rifle, and helmet, have previously been noted to yield a reduction in marksmanship and grenade throw distance as compared to pre-march measures, whereas no differences in those measures were found between loaded and unloaded prior to the march (Knapik et al., 1991). These findings indicate that while the load itself may not interfere with performing physical tasks, the physical fatigue that it induces does have a negative effect on soldiers. Based on this data, the fatigue inducing effects of a new system that increases soldier load, such as armor systems, may be of as much interest as the initial performance reducing effects of wearing the system alone. Characterizing the way in which the system increases fatigue could lead to improvements in design or use of the system that mitigate these detrimental factors.

2.2 GAIT

The study of gait can be used to diagnosis musculoskeletal pathologies or to evaluate effects of environmental factors on the musculoskeletal system, such as loading due to backpacks and body armors. Dismounted soldiers are required to walk or run long distances with substantial loads made up of ballistic armor, load bearing vests with essential items such as ammunition, and backpacks carrying supplies such as food, water, and clothing. Gait analysis has show that loads such as armor, vests, and backpacks can have a significant effect on the performance and patterns in walking and running (Knapik, 2001; Knapik et al., 1997; Quesada et al., 2000; Pandolf et al., 1977; Harman et al., 2000).

The gait cycle is broken down into phases, separated by gait events (**Figure 2**). The gait cycle in biomechanical analyses, classically begins with the heel of one foot contacting the ground, known as the heel strike, and ends with the following heel strike by the same foot

(Jensen & Schultz, 1977). The stance phase of gait, which accounts for about 60% of the gait cycle in walking and a majority of the muscle activity, begins with heel strike and ends with toe off, as the same foot pushes off the ground for propulsion forward (Jensen & Schultz, 1977). The swing phase, accounting for the remaining 40% of the cycle, then follows toe off and ends with the foot again makes contact with the ground at heel strike. This pattern occurs for each leg, with swing phase of one leg taking place during stance phase of the other leg. There is, of course, some overlap between stance phases since they are longer then swing phases. This overlapping period when both feet are in contact with the ground is called double support, as opposed to the single support time when only one foot is in contact with the ground to support the weight of the body. During walking, at least one foot is in contact with the ground at all times. Running is differentiated by the lack of double support time and the addition of a flight phase, during which no part of the body is in contact with the ground (Jensen & Schultz, 1977). Each flight phase occurs between the toe off of one foot and the subsequent heel strike of the opposite foot. Running gait also differs from walking in that there is a reduction in stance phase and an increased percentage of the cycle occurring in swing phase (Jensen & Schultz, 1977).

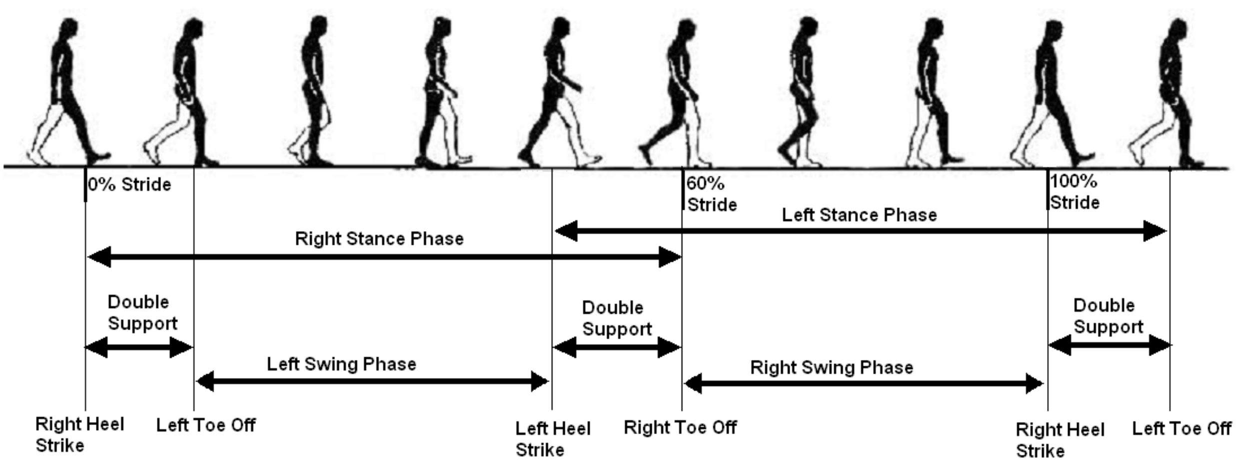

Figure 2. Human walking gait cycle, with heel strikes and toe offs separating phases of gait.

Regardless of the rate of ambulation, i.e., walking or running, the distance between consecutive heel strikes defines the step length. Stride length refers to the distance between successive heel strikes with the same foot. The frequency with which steps occur is designated as the cadence. Gait speed, or gait velocity, is the product of the cadence and the step length (Jensen & Schultz, 1977). These measurements, along with displacements, velocities and accelerations of body segments in human movement, are known as kinematics.

In order to measure how hard the human body is working to achieve those movements, one must measure energy expenditure (Wasserman et al., 1987). One non-invasive means to calculate the energy expenditure and efficiency of body is by sampling the amount of oxygen and carbon dioxide in the air exhaled by the individual during a given task. Since oxygen must be combined with hydrogen to release energy as foods are metabolized within the body, the amount of energy used by the body is directly linked to the amount of oxygen it consumes and converts to carbon dioxide (Fox et al., 1989). The oxygen consumed and carbon dioxide released must pass through the respiratory system, and so, the expired gases reflect the oxygen usage of the cells, including muscle cells, and can be used to measure the work rate of the body (Wasserman et al., 1987). Sampling the expired gases, therefore, is a practical form of indirect calorimetry to measure energy expenditure for a task (Dechert et al., 1988). By measuring the changes in volume of oxygen consumed (VO_2) and the carbon dioxide expired while walking and running, the differences in energy cost due to changes in gait can be analyzed (Thomas et al., 2009).

Walking is a very energy efficient form of locomotion (Steudel-Numbers, 2003). This is due, in part, to the inverted pendulum-like movement of the body’s center of mass over the foot with each stride (Cavagna & Margaria, 1966). The transition between the two inverted pendulums leaves the forward kinetic energy and the potential energy out of phase as energy is exchanged between the two. The inverted pendulum motion doubles gait efficiency, as compared to a flat gait in which the center of mass remains on a flat trajectory, parallel to the

ground, rather than oscillating vertically as in normal healthy gait (Massaad et al., 2007). The efficiency of human locomotion goes beyond the mechanics of movements. Each step to step adjustment made subconsciously during walking or running also contributes to the energy cost of locomotion. Without any conscious effort, humans alter their gait so as to minimize the metabolic cost of locomotion under the imposed parameters (Umberger & Martin, 2007; McNeill, 2002; Donelan et al., 2001; Thelen & Anderson, 2006). When allowed to choose their own pace, humans will naturally prefer to walk at the speed which their metabolic energy expenditure is the lowest (Umberger & Martin, 2007). When the desired speed of locomotion reaches the point at which running is more economical than walking, the transition is made to a run without any thought. At any given speed, stride length (McNeill, 2002) and width (Donelan et al., 2001) are naturally chosen so as to minimize energy cost. Each muscle activation and duration of activation is carefully timed to optimize efficiency as well (Thelen & Anderson, 2006).

The natural efficiency of gait has been shown to greatly reduce as joint motions move away from those of normal healthy gait. Walking in a crouched stance with knees and hips in constant flexion can double the energy cost of locomotion (Carey & Crompton, 2005), while limiting the range of motion of the knee alone in health patients can increase the energy expenditure of walking by as much as 23% (Hanada & Kerrigan, 2001; Mattsson & Brostom, 1990, Duffy et al., 1997). Similarly, immobilization of the ankle with a brace or orthoses can result in an increase in energy cost of 26% (Herndon et al., 2006). Conversely, bringing the gait kinematics of patients suffering from orthopedic pathological, such as cerebral palsy and hemiplegia, back into the range of normal, healthy kinematics by use of orthoses results in reduction in energy expenditure in walking (Brehm et al., 2008; Buckon et al., 2004). With such high efficiency in natural, healthy gait, it is easy to understand how even the slightest disturbance can cause an increase in energy cost.

2.3 LOAD CARRIAGE

Soldiers in the field often carry large amounts of weight on their body when on missions. The majority of this weight on the body is comprised of ammunition, food, water, and body armor. The ammunition, food, and water can be carried either in or on a load bearing vest, in a backpack, or distributed across both. Other items needed for specific missions or particular environments can be included on the load bearing vest or in the backpack as needed. Missions can last from a few hours to 72 hours without opportunities to restock supplies. This leads to soldiers carrying a wide range of weights and weight distributions on their body. The act of having to transport theses load themselves, i.e., walking or running with the loads for any period, is known as load carriage (Department of the Army, 1990). During load carriage on the battlefield, the loads carried by soldiers on average is 40 kg (Knapik et al., 1990), and can range from 25 kg to over 60 kg, depending on the mission objectives and duration (Hasselquist et al., 2005). The energy expenditure of gait with such loads, as measured by oxygen consumption, has been of specific interest as soldiers are required to work at a high capacity in battle even after long, arduous marches carrying their heavy loads. Anything that could further deplete their energy levels or increase the onset of fatigue must be carefully characterized. The Army and its research centers strive to mitigate these negative effects and continually endeavor to improve all facets of soldier performance. As such, much of the existing research on loading and soldier performance has concentrated on quantifying the physiological effects and metabolic cost of load carriage (Knapik et al., 1996).

2.3.1 Metabolic Cost and Load Carriage

The existing studies in the area of load carriage confirm that physiological energy expenditure, also known as the metabolic cost, of soldiers walking with a backpack load increases as the mass of the load carried, the walking speed, or the grade of incline increases

(Pandolf et al., 1977; Giovani & Goldman, 1971; Polcyn et al., 2001; Sagiv et al., 1994; Soule et al., 1978; Keren et al., 1981; Goldman & Iampietro, 1962). Even while standing still, an increase in loading on the body results in increased energy expenditure, as was measured by the volume of oxygen consumed (VO_2) (Pandolf et al., 1977). Hughes and Goldman (1970) found that even though volunteers' preferred walking speed decreased as load increased incrementally from no load to 60 kg, energy cost still increases with load despite the reduction in speed. Even at loads of 15% body mass, statistically significant changes in metabolic cost have been observed (Quesada et al., 2000).

The center of mass placement of a load was also found to play a factor in energy costs. Using a custom designed experimental backpack (**Figure 3**), Obusek at al. (1997) found that manipulating the position of the center of mass (COM) of the pack while maintaining a constant mass had a significant effect on the metabolic cost of walking and running. By packing heavy objects higher in a backpack to position the center of mass (COM) of the load up higher on the back, the metabolic cost of walking can be significantly reduced, as compared to carrying the same load mass with the COM lower on the back (Obusek et al., 1997; Stuempfle et al., 2004). Reductions in energy expenditures were also found for pack loads with a COM that was close to the body, as opposed to those farther away from the body (Obusek et al., 1997). Comparisons of backpack loading to more balanced loading systems found that the balanced load systems tended to diminish metabolic costs of load carriage. These balanced load systems moved the load COM further forward than a backpack alone by distributing the load between a backpack and a pocket on the front of the torso (Legg & Mahanty, 1985; Lloyd & Cooke, 2000). Decreases in walking metabolic costs resulting from well balanced loads were even greater when walking on incline up to 20% gradients (Lloyd & Cooke, 2000). The metabolic cost can be further improved by positioning the evenly balanced torso load close to the body (Coombes & Kingswell, 2005). This may be due to the reduction in the moment of inertia of the load relative to the body, as extending the moment arm could increase the force the body must apply to the

load in order to control it. When the load carried is well balanced and evenly distributed about the torso, the energy expenditure per kiligram of load has been found to be constant up to 70 kg (Soule et al., 1978; Goldman & Iampietro, 1962). When the load added was evenly distributed so that did not disturb the center of mass of the person, the energy expenditure per kilogram of load in walking was also found to be no different than the energy expenditure per kilogram of body weight (Goldman & Iampietro, 1962, Soule & Goldman, 1969). In evaluating the effects of novel loads on energy expenditure this information can be applied to appraise whether the mass of the load alone is the cause of the increased energy expenditure or if the design and distribution of the load is playing a role. Based on this information, researchers developed a predictive model for metabolic cost was created which takes into account the subject's body mass, the mass of the load carried, the speed of walking, the grade, and a terrain factor (Giovani & Goldman, 1971; Pandolf et al.,1977; Duggan & Haisman, 1992). This model, however, assumes steady state, and does not take into account the increases in metabolic costs that occur when the body is pushed beyond 50% of maximal physical work capacity, at which point physical fatigue begins to set in (Epstein et al., 1988). Work intensity is found to increase over time, and metabolic costs gradually elevate due to fatigue. Because of this, caution must be used when applying the model to heavy loads and long durations (Epstein et al., 1988, Patton et al., 1991).

As these results indicate, the placement and physical properties of loads applied to the body, not just weight alone, can affect the energy levels need for moving that load with the body. Though not all of the causes of these increases in energy costs have been identified, some of the changes have been linked to changes in gait patterns and the way the body must position itself to stabilize and propel the loads.

Figure 3. Experimental military backpack for load carriage research. The customized “ALICE” backpack was designed specifically for laboratory testing of the effects of center of mass (COM) position on gait and metabolic cost. This prototype allowed for quick adjustment of the COM of the load by cranking the lead block containing load compartment up and down the frame of the pack.

2.3.2 Gait Kinematic and Load Carriage

Studies have indicated that changes in gait patterns directly relate to energy costs in walking (Cotes & Meade, 1960). Much of the changes in metabolic cost that occur with load carriage are caused by the increased forces that the body must generate to propel and control a larger mass (Gottschall & Kram, 2003). Studying the changes in walking and running patterns that occur can help to draw out the factors that contribute to such variations.

Studies on the effects of torso-borne loads on walking kinematics have found that stride length and swing time are inversely effected by loading, while stride rate and double support time were directly proportional, when walking speed was fixed between loads (Kinoshita, 1985; Martin & Nelson, 1986). When speed was not fixed, the absolute time of double support was not changed, though subjects’ preferred walking speed reduced as the load carried was increased (Smith et al., 1960), which may indicate an increase in the percentage of the gait cycle spent in

double support time. This increased double support time may contribute significantly to the alterations in metabolic costs that come with loading. When considering gait as a pair of inverted pendulums, the double support time is the period of transition between the two, during which energy is lost between controlling the mass and propelling it. The braking force of the front leg, in this phase, is doing negative work, which the propulsion leg in the rear must overcome (Donelan et al., 2002). It is believed that double support time increases and stride length and swing time decrease as a means of providing increased stability needed to control the additional mass of the load as well (Kinoshita, 1985). These changes in temporal gait parameters were greatest for loads with COM low on the back as opposed to high on the back, indicating an increased destabilization resulting from the low COM backpacks (Singh & Koh, 2009).The increased double support time also aids in reducing the amount of time that each leg must support the weight of the load alone during single support, lowering the mechanical strain each leg must endure. In order to maintain fixed speeds while increasing double support time and decreasing step length, step frequency was forced to increase (Kinoshita, 1985; LaFiandra et al., 2003). This increased step frequency is one of the factors in the decrease in energy efficiency observed in load carriage (Pierrynowsi et al., 1981). While double support time does not exist in running, and, therefore, cannot increase, trends of reductions in stride length have been found to occur (Coombes & Kingswell, 2004).

Changes in joint kinematics as a result of loading have been discovered in the trunk, ankle, knee, and hip. Forward inclination of the trunk (lean) has been found to increase as load mass is increased in backpack loads (Polcyn et al., 2001; Martin & Nelson, 1986; Kinoshita, 1985; Goh et al., 1998; Orloff & Rapp, 2004; Attwells et al., 2006). The position of the COM of the load in particular directly affects the lean angle, as the body must position the system COM, including both the load and the body itself, over the base of support, i.e. the feet (Polcyn et al., 2002). Attwells et al. (2006) also found that head inclination changed with such loads, possibly assisting in counterbalancing the loads. The lack of lean angle change accompanying loads

distribute evenly across both the front and the back of the torso (Martin & Nelson, 1986; Kinoshita, 1985) and the hyperextension posture associated with the carriage of anterior loads (Anderson et al., 2007) both seem to verify the COM repositioning as the cause of load associated leaning. Since both forward inclinations and hyperextension postures increase the strain on the lower spine and increase chance of injury (Goh et al., 1998), such changes to posture should be monitored whenever loads are applied to the torso or head.

Changes in ankle kinematics were uncovered by Kinoshita (1985), when it was observed that heavier loads resulted in a longer period of rotation of the foot in the sagittal plane. This was supported by later studies which found significant changes in both peak dorsiflexion and peak plantar flexion during stance phase after completing a 40 min march with loads of 15% and 30% body weight, about 12 kg and 24 kg on average (Quesada et al., 2000; Attwells et al., 2006). These adjustments to maximum plantar flexion and maximum dorsiflexion result in a larger total range of motion of the ankle angle in gait (Attwells et al., 2006). It was concluded that this longer period of rotation of the foot and increased plantar flexion showed that loading impeded the lever action employed by the body at toe off for propulsion, and increased mechanical stresses on the foot (Kinoshita, 1985). This increased stress may be a cause of the reduced step length and increased double support time (Kinoshita, 1985).

Knee motions were similarly affected by loading. As the weight carried escalated, the result was an increase in knee flexion, particularly during the initial part of the stance phase (Kinoshita, 1985; Polcyn et al., 2001; Quesada et al., 2000; Attwells et al., 2006). It was hypothesized that this is due to the knee flexors acting as a shock absorber, reducing the impact forces that would be associated with the added load and body mass being transferred as the foot made contact with the ground (Kinoshita, 1985). This increased knee flexion also resulted in a greater dorsiflexion at mid stance (Kinoshita, 1985). Using military personnel carrying military relevant loads, Attwells et al. (2006) found that knee range of motion in walking

gait rose as load increased due to not only the increased flexion at heel strike and loading, but also due to a greater knee extension during the toe off, or propulsion phase.

Carriage of torso mounted loads was also found to cause increased hip range of motion in the sagittal plane (LaFiandra et al., 2003, Lee et al., 2009; Attwells et al., 2006). As with the knee, the alterations in range of motion at the hip result from increased flexion during the heel strike phase and increased extension at toe off (Attwells et al., 2006). It was stated that this adjustment to range of motion is in compensation for the decreased pelvic rotation due to backpacks increasing the transverse plane moment of inertia of the torso, which counterbalances the angular moment of the legs in walking. It was hypothesized that the increased hip excursion, however, is not enough to make up for the loss of pelvic rotation's contribution to stride length, and thus, stride frequency must increase as well in order to maintain walking speed (LaFiandra et al., 2003).

Adjustments in kinematics appear to be actions taken by the body in an attempt to maintain stability and alleviate some of the mechanical stresses load carriage can cause (Kinoshita, 1985; LaFiandra et al., 2003; Polcyn et al., 2001), even if they must do so at the cost of energy efficiency in gait.

2.3.3 Extremity Loading

Applying a load to the hands or wrists during locomotion comes with larger energy consequences that affixing the same mass to the torso. Even handheld weights as small as 1.36 kg have been found to increase metabolic cost of walking as compared to walking with no added weight (Graves et al., 1987). The effects of upper extremity loading on metabolic cost, however, are dependent upon the mass applied and speed of ambulation. Loads of 7 kg carried in each hand, at walking speeds up to 5.6 kph, were found to elicit and energy cost 1.9 times higher than it would if carried on the torso (Soule & Goldman, 1969). At a walking speed of 5.6 kph, a 4 kg mass carried in the hands also comes with a cost 1.9 times higher than a torso load

of the same mass, but when speed is reduced to 4.8 kph, the same load induces only 1.4 times the metabolic cost to carry (Soule & Goldman, 1969; Miller & Stamford, 1987). The metabolic cost of running was found to be unchanged with handheld weights until the mass of the weights reached 2.27 kg or higher (Owens et al., 1989; Claremont & Hall, 1988). Soule and Goldman (1969) postulated that the lower level of metabolic cost increases that arise at low walking speeds may be the product of less physical work being done as a reduction in arm swing occurs to compensate for the load. The suppression of arm swing, however, has been observed to cause an increase in metabolic cost of gait at speeds of 2.91 mph, and is most likely not related to a reduction in metabolic cost (Umberger, 2008; Yizhar, 2009). Though the relationship between hand loading and speed on metabolic cost of locomotion is not fully understood, the differences between hand and torso loading may be similar to the increase in metabolic cost associated with loads that are further from the body creating a larger moment of inertia which the body must overcome to maintain control of the load, as Coombes and Kingswell (2005) found. Given that loads applied to the hands and wrists have differing results than torso loads, Pandolf's (1977) equation for predicting metabolic cost for a given load cannot be applied to extremity loading (Duggan Haisman, 1992). While differences have not been seen in the metabolic cost between placement of loads at the wrists and hands (Graves et al., 1987), little is known about more proximal loads to the upper extremities. More information is need on the metabolic costs associated with loads attached to the upper limbs.

As with arm loading, the body also responds to loading of the lower extremities differently than it does to torso loads. Walking with small loads, such as that of a boot or heavy shoe (0.35 to 1 kg), added to the feet have been found to increase metabolic cost between 1.9 and 3.1 as much as if the same mass was added to the torso (Holewijn et al., 1992; Burkett et al., 1985; Martin, 1985; Miller & Stamford, 1987). Walking with higher weights on the feet, 3.5 to 6 kg, was found to increase metabolic cost 4.7 to 6.4 times higher than carrying the load on the torso, depending on speed (Legg & Mahanty, 1985; Soule & Goldman, 1969). Similar results

are found in running (Burkett et al., 1985; Martin, 1985; Claremont & Hall 1988). Masses as small as 150 g applied to each foot during running have been found to result in statistically significant increases in metabolic cost of running (Divert et al., 2008). Increasing loading at a constant position on the legs reduces preferred running speed in an attempt to preserve metabolic cost levels (Bhambhani et al., 1990), much as torso loading was found to do. In both walking and running, leg loads were found to reduce stride rate and an increase in stride length and swing time (Martin, 1985; Browning et al., 2007). This is contrary to the effect of loading the torso which has been consistently found to reduce stride length (LaFiandra et al., 2003; Kinoshita, 1985; Martin & Nelson, 1986). It is theorized that these kinematic changes are the result of the body energetically optimizing stride rate based on the pendulum oscillation dynamics of the swing leg (Holt et al., 1990). In this pendulum model, once the limb enters swing phase, it naturally swings as a passive pendulum, oscillating at the frequency that minimizes metabolic cost (Holt et al., 1990).

The effect of mass added to the feet has received great attention, with foot wear manufacturers such as Nike regularly funding such research due to its implications in athletics shoe (Frederick, 1985; Landry et al., 2007a; McKean et al., 2007; Landry et al., 2007b; Grau et al., 1999). Less research, however, has been done in the way of thigh and shank loading, especially in healthy, able-bodied individuals. What little work has been done has proven that, in both walking and running, the more distally the load was place, the higher the resultant metabolic cost increase was to move with the load, with foot loading having the highest cost (Royer & Martin, 2005; Browning et al., 2007). Loading the thighs, in particular, was relatively inexpensive, as the metabolic cost associated with it was very close to that of carrying the same load on the torso (Browning et al., 2007). A load of 16kg, divided evenly between the two thighs, increased the net metabolic cost (total – resting) by only 14% as compared to carrying the same load around the waist, whereas the same load applied to the feet resulted in a 48% rise in net metabolic cost (Browning et al., 2007). This more distal placement of the mass increases the

moment of inertia of the mass about the hip, while maintaining a constant mass of the load. Treating the leg and load as a single system, Royer and Martin (2005) found that increasing the moment of inertia of the leg-load system 5% from a baseline load by moving a constant mass distally down the shank induced a similar rise in metabolic cost as maintaining the moment of inertia while increasing only the mass 5%. These manipulations also found that increases in moment of inertia caused increased swing time, as had been found in foot loading (Martin, 1985; Browning et al., 2007). The increase in mass while maintaining a constant moment of inertia about the hip, however, resulted in a decrease in swing time. This supports the Holt et al. (1990) theory of the optimized period of oscillation based passive pendulum model for the swing leg (Royer & Martin, 2005). Clearly, in loading of the lower limbs, the placement and distribution are as influential as the mass of the load itself, and must be taken into consideration.

2.3.4 Extremity Armor

After the success of the IBA vest (Mazurek & Ficke, 2006; Pollak, 2008), the United States Department of Defense has begun investing in the development of new ballistic armor systems built to protect the arms and legs (NRL Press Release, 2006). Little investigation into the effects of such extremity armor on the human has been completed (Hasselquist et al., 2008a; Hasselquist et al., 2008b).

Hasselquist et al. (2008a) compared three types of extremity armor systems which were designed to protect the arms and legs from ballistic threats, i.e. gunfire and shrapnel, much as the IBA vest does for the torso. Each of these three extremity armor systems incorporate the current standard ballistic armor vest, the IBA vest, expanding the total area of ballistic protection with modular attachments that connect to the IBA in some fashion. The three models of extremity armor were similar in weight (5.6 to 6.4 kg), and each covered some percentage of both the arms and the legs. The materials, mechanical properties, and attachment system of each armor system differed greatly, however. The results of the study indicated that wearing

extremity armor increased the metabolic cost of running and walking by about 7% and 17%, respectively. Despite very different designs, some resembled sleeves hanging from the IBA while others were more of curved plates attaching to the limbs with Velcro straps, there were no significant differences in energy expenditure between the three forms of extremity armor. The ground reaction forces at heel-strike and toe off were found to be significantly higher with use of extremity armor as compared to use of the IBA alone as well, but again, no statistical differences were seen between extremity armor systems. The increase in ground reaction forces recorded indicates an increase in forces being applied through the body, which could potentially increase risk of musculoskeletal injury to soldiers wearing such a system. The evaluations also found that stance time, double support time, and stride width during walking were increased with use of armor on the arms and legs. Swing time was found to be significantly shorter with only one of the extremity armor systems. While increased stance and double support time match what is expected with loading (Kinoshita, 1985; Martin & Nelson, 1986), the reduction in swing time is contrary to what is expected with lower limb loading (Holt et al., 1990; Royer & Martin, 2005), and may be due to design characteristics other than mass.

While there is a dearth of physiological or biomechanical research reported in the literature, the results of testing the effects of heavy clothing may also be of interest. Teitlebaum & Goldman (1972) evaluated the consequences of extreme cold weather military clothing on metabolic costs in walking and running, at speed of 5.6 kph and 8.0 kph. They discovered that 11.19 kg, seven layer clothing ensemble increased metabolic cost in walking and running by 18% and 14%, respectively, as compared to carrying an equivalent mass of 11.19 kg in a belt around the torso. Since the metabolic cost increases were far higher than what would be expect even if the mass was positioned at the ends of the extremities (Giovoni & Goldman, 1971), it was hypothesized that the friction between layers of clothing and the increased stiffness at the joints due to the clothing's bulk may be the reason for the majority of the energy increases (Teitlebaum & Goldman, 1972). This was supported by recent findings made in testing

metabolic cost penalties of walking in personal protective clothing for chemical environments, in which weight alone did not account for the increased metabolic cost of walking in the protective clothing (Dorman & Havenith, 2009).

Previous studies involving extremity armor or clothing could only stipulate on the associate change in joint kinematics that may have occurred. This is because the material covering the joints would interfere with the classical means of collecting the kinematics of the body segments, such as optical motion tracking markers and goniometers. Attempting to track joint movements in such a study meant that the motion tracking markers or goniometers would have to be attached to the extremity armor, clothing, or other material covering the joint. Placement of the kinematic tracking device over such obstacles greatly increases error between movements measured by the device and the underlying movement of interest in the bones. This increased error is due to the fact that the kinematic measurement equipment would be measuring the motion of the material it is attached to, which may have several degrees of freedom from the actual body segment of interest which it is placed over, creating a motion artifact. Recent advancements made to overcome the soft tissue motion artifacts associated with optical motion tracking, however, can help to eliminated some of the error in motions that are collected (Lu & O'Connor, 1999). These systems, intended to reduce the motion artifact of soft tissue such as muscle and fat which may move over top of the bone of interest, can impose joint constraints on the marker movements based on a multi-link musculoskeletal model, and optimize kinematics to reduce global error (Lu & O'Connor, 1999). The resulting segment kinematics are free from motions which would be impossible for healthy joints to achieve, resulting in data that is much closer to the desired measures of bone and joint movements.

Each of the systems involved in the testing done by Hasselquist et al. (2008a) had modular components, allowing for various levels of protection to worn. In the partial coverage configuration, the lower arm and lower leg section of the ballistic armor are removed, leaving those limb segments exposed while still protecting the upper arms and thighs. While

Hasselquist et al. (2008b) completed an investigation of extremity armor systems exploring the modularity of the systems, the cause of the resulting increases in metabolic cost of walking with increasing coverage was left unanswered. Since previous studies have shown that more distal loads on the extremities have larger metabolic penalties (Royer & Martin, 2005; Browning et al., 2007; Graves et al., 1987; Martin, 1985), the placement of the extremity load may be the primary factor. Evaluating whether the distal placement of the mass of the lower arm and lower leg sections of the extremity armor or some other effect of the armor on gait kinematic and range of motion were the source of the increased metabolic cost could help armor designers to make improvements that negate the effect of these factors. There may be an optimal point between energy cost and armor coverage which can be found through further biomechanical and physiological research.

The extremity armor chosen for the current study was the Integrated Dismounted Armor System (IDAS™), from Med-Eng Systems Inc. (Ashburn, VA). This armor is designed for military and law enforcement personnel to be flexible and impede joint movement as a little as possible by leaving the area immediately around the joints uncovered by the armor. At 5.6 kg (12.3 lbs), the full body configuration of the system covers much of the upper and lower arms, as well as the thighs and shanks, with Type III-A armor protection (Allen-Vanguard, 2010). Type III-A ballistic protection is certified to protect against .44 caliber magnum and 9mm submachine gun munitions (Ballistic Resistance of Body Armor NIJ Standard-0101.06, 2008). The IDAS is a modal extremity protection system designed by Med-Eng Systems, Inc (Ottawa, Ontario, Canada) for mounted and dismounted operations. The system includes arm components attached to a vest designed to be worn under the IBA vest. The leg components are similarly supported by a belt and suspenders which are worn under the IBA vest as well. In the partial coverage configurations, the IDAS offers armor protection to the upper arms (shoulders to elbows) and the thighs. Additional armor is then attached for the full coverage configuration, offering protection to the lower arms (elbow to wrist), and lower legs (shanks). The lower leg

and lower arm pieces attach to their upper counterparts by straps with hook-and-loop fastener tapes. The components and coverage of the IDAS extremity armor system can be seen in **Figure 4**.

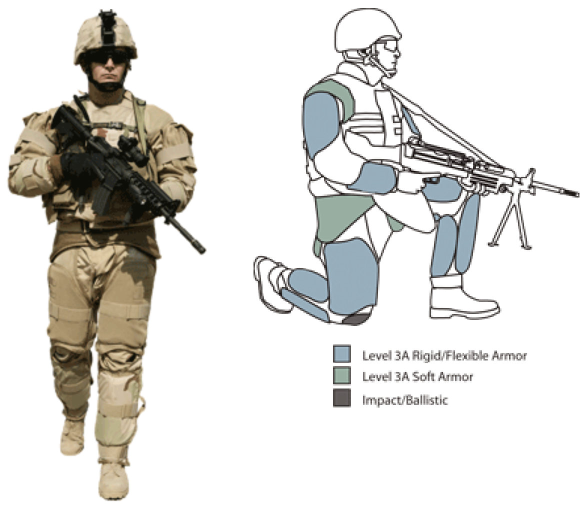

Figure 4. Photograph and diagram of the Integrated Dismounted Armor System (IDAS™) with armor vest and helmet .

Table 1. IDAS™ Component masses and total mass. Upper arm components were connected to each other, and could not be measured individually, as were pelvis/thigh components.

IDAS COMPONENT (Large)	**MASS (kg)**
Arms/Shoulders	1.9
Forearms	0.25
Upper arms (2)	1.4
Legs/Pelvis	4.55
Shanks	0.75
Pelvis/Thighs (2)	3.05
Total IDAS System	**6.45**

CHAPTER 3: HYPOTHESIS AND SPECIFIC AIMS

It was hypothesized that in addition to changes in oxygen consumption and temporal gait parameters due to the wearing of extremity armor in walking and running, changes in joint kinematics also result from the use of extremity armor. Additionally, it was hypothesized that these changes in gait patterns and increases in metabolic cost scaled to total mass would be significantly reduced by removing the most distal components of the modular extremity armor, which cover the lower leg and lower arm.

Specific Aim 1: Quantify Extremity Armor Effect on Joint Kinematics

Motion capture data of subjects walking and running on a treadmill was analyzed to determine the joint angles at the ankle, knee, hip, and trunk with extremity body armor configurations and no armor condition. For each stride, the subject's minimum and maximum joint angle were measured, and from this the range of motion for each stride was calculated. Changes in joint angles and ranges of motion were used to determine if the armor load worn had a significant effect on gait mechanics.

Specific Aim 2: Characterize Differences in Effect of Armor Coverage on Gait Parameters and Metabolic Cost

Motion capture data, oxygen consumption data, and kinematic data from walking and running while wearing extremity armor in the full and partial configurations were compared. This evaluation determined whether the removal of the lower arm and lower leg potions of the armor significantly reduced metabolic cost and changes in gait kinematic while still maintaining some level of increased body coverage as compared to the IBA vest alone.

Specific Aim 3: Compare Percent Body Coverage with Each Armor Configuration

Subjects were imaged in a 3-dimensional scanner with and without armor. By calculating the percent body coverage that the extremity armor provides in the partial configuration and the full configuration, an optimum balance between added load on the body and increased ballistic protection can be found.

CHAPTER 4: MATERIALS AND METHODS

4.1 PARTICIPANTS

The target sample population of this study was infantry Soldiers, who are most often in direct ground combat situations requiring ballistic protection. While it is recognized that female Soldiers are also often required to wear ballistic protection while on duty, Army Regulation 600–13 states that females are prohibited from training for or serving in combat infantry positions which routinely participates in direct ground combat. Due to this fact, being male was an inclusion criteria.

The 15 participants recruited for the data collection of this study were U.S. Army enlisted men serving as human research volunteers assigned to Headquarters Research and Development Detachment, U.S. Army Natick Soldier Systems Center, Natick, MA. Due the physical stress of the testing, volunteers were required to be between the ages of 18 and 35 weighing no less than 61.2 kg (135 lbs). Volunteers were also excluded if they had any history of herniated intervertebral discs, or any other orthopedic injury that may limit motion of shoulder, hip, knee, or ankle. All volunteers selected had recently completed Advanced Individual Training (mean time in service: 6 months). Five of the volunteers were infantrymen (MOS 11B). The other seven were unit supply specialist (MOS 92Y). The demographic information for the 15 volunteers can be seen in **Table 2**.

Prior to testing, the data collection protocol as reviewed by the Human Use Review Committee, the Institutional Review Board of record at Natick Soldier System Center. All participants cleared physical examinations and clinical reviews of their medical records. Any volunteers with existing musculoskeletal injuries were excluded from testing. After being informed of the nature of the testing and all possible risks involved, participants signed Consent to Participate in Research forms (**Appendix B**).

Table 2. Demographics of Study Participants (N = 15).

Variable	Mean (St. Dev.)	Minimum	Maximum
Stature (m)	1.78 (0.68)	1.67	1.91
Weight (kg)	85.1 (8.83)	73.5	103
Age (yr)	21.7 (2.90)	19.1	27.7
Time in sevice (yr)	0.54 (0.12)	0.40	0.80

4.2 Testing Overview

In addition to the trials analyzed in this paper, it should be noted that a series of other physical tasks were performed during each testing session. This additional workload was due to the fact that the data analyzed in this study were collected as part of a greater study on physical modeling of load and armor effects on the human body. Most notably, these additional tasks included 4 minutes of walking (3 mph) at an 18% incline and 4 minutes at an 18% decline. These additional walking tasks followed after the walking data for this study was collected, but prior to each running trial. Between the walking at grade and attempting the running trial, each subject was given a 10 minute seated resting period. A complete list of the physical tasks completed during each testing session, in the order performed, can be found in Appendix A.

Each volunteer attended four sessions lasting 1.5 to 3.5 hours each in the Center for Military Biomechanics Research at the Soldier Systems Center, Natick, MA. The first lab session was simply an orientation, while all data collection took place during the three subsequent testing sessions. The orientation session lasted approximately 3.5 hours, during which the volunteers were sized for clothing and equipment and then familiarized with the testing procedures and all testing equipment. The familiarization included walking and running on the treadmill for 5 to 10 minutes (Tseh et al., 2000; Keefer et al., 2005), and all other physical activities that were to be done in testing. Familiarization was done with each of the three armor conditions as well, in order for the subjects to become acquainted with fit and weight of the armor being used (Smith & Martin, 2007). This familiarization session was given in order make

the volunteers comfortable with the testing conditions and the testing environment to mitigate the effects of familiarization on the volunteers' biomechanics. It has previously been found that exposure to novel loads and testing conditions prior to data collection can reduce oxygen consumption and improve kinematic data stability (Schiffman et al., 2008). Research shows that kinematic learning curves exist, in which subjects exposed to the novel loads and testing conditions must acclimate their gait to the new factors in order to reach a steady state.

After completing the orientation session, each subject participated in three session of testing; one for each armor condition. All testing sessions took place between 0700 hours and 1730 hours, with each subject participating in either a morning session or an afternoon session, but never both in the same day. Only one participant took part in testing during each session. Subjects were advised to eat regular meals prior to test sessions and were asked to refrain from alcohol and physically strenuous activity 24 hours prior to each testing session.

The volunteers reported for each session in their physical training (PT) uniforms with their combat boots. All other clothing and equipment was provided by the investigators. For each data acquisition session, a volunteer wore one of the three armor conditions: no armor, partial extremity armor coverage, or full extremity armor coverage. For the three testing sessions, the volunteers were assigned to one of the six possible orders of exposure to the three armor conditions at random.

The three testing sessions were divided so that each session would include all physical activities done in the same order, with the same armor condition for an entire session. Subjects were asked to complete the four sessions in the lab on consecutive days, with no more than one session per day. If unable to complete all four sessions on consecutive days due to scheduling issues, equipment failure, or minor health concerns, the subject were scheduled to complete the remaining session(s) as soon as possible.

4.3 ARMOR AND CLOTHING COMPONENTS

Volunteers were outfitted with one of three armor conditions for each of the three testing sessions. In all conditions, subjects were asked to wear their military issued physical training (PT) shirt, PT shorts, socks, and combat boots, which combine to a total weight of approximately 2.0 kg. In the no-armor condition, this was all that was worn. For the two conditions in which extremity armor is worn, the subjects also wore an Interceptor Body Armor (IBA) outer tactical vest with military relevant load, an Advanced Combat Helmet (ACH), and an extremity armor system. For this testing, the collar, groin protector, and two small arms protective insert plates (one front and one back) were added to the IBA vest. In order to match battlefield relevant loading conditions, pouches containing mock ammunition magazines and grenades were attached to the front of the IBA. These mock items contained no explosives or propellants, but matched the mass and volume characteristics of their battlefield counterparts. The weight of ballistic helmet used, the ACH, varies by size from 1.33 kg to 1.5 kg (small to large), and secures to the soldiers head via a four point chin strap (Interceptor Body Armor (IBA), 2009). The total weight of the full IBA system used for testing, including attachments, and the ACH helmet was approximately 21.2 kg.

The modular Integrated Dismounted Armor System (IDAS™) extremity armor system used for this testing adds a weight of 5.6 kg in full coverage configuration, while the partial coverage configuration adds only 3.6 kg to the soldier borne load. These two configurations, along with the no armor configuration, encompass the three armor conditions that were used in testing.

Only one extremity armor system was used in this study due to the findings of Hasselquist et al. (2008a), who found no significant differences between extremity armors systems except in maximal performance tests, which were not attempted here. The IDAS

system chosen was one of the three systems evaluated by Hasselquist et al., and, as such, the findings here should be at least somewhat applicable to the other systems which they tested.

Table 3 contains a summary of the components and weights of the three armor conditions being used in the testing sessions. The weights are approximate, as there may be slight variations due to differences in the sizes worn by each subject.

Table 3. Components and masses of testing conditions.

Condition Components	Mass (kg)
No Armor	
Basic (shorts, socks, combat boots)	2.0
Basic + M4 Carbine	4.3
Partial Extremity Armor Coverage	
Basic (T-shirt, shorts, socks, combat boots, helmet, IBA, ammo/grenade pouches, IDAS upper arm and upper leg extremity armor)	24.9
Basic + M4 Carbine	27.2
Full Extremity Armor Coverage	
Basic (T-shirt, shorts, socks, combat boots, helmet, IBA, ammo/grenade pouches, IDAS upper and lower arm and leg extremity armor)	26.9
Basic + M4 Carbine	29.2

4.4 Testing Equipment

The treadmill that was be used for the walking and running activities was a custom built force plate treadmill, designed and fabricated by AMTI (Watertown, MA). Using a treadmill rather than ambulating over ground allows for the collection of data from many strides in a very short time period. Data collected on a treadmill has been shown to be a good representation of walking overground in healthy individuals, with no significant differences being found in joint kinematics, temporal parameters, or oxygen consumption for walking or running (Lee & Hidler, 2007; Bessett et al., 1985, van Ingen Schenau, 1980). The treadmill used in this study is capable of reaching belts speeds of 4.83 m/s and grades of +/- 25%, but remained at 0% grade

for this study. The treadmill is equipped with two synchronized treadmill belts aligned in series (front, back). The gap between these two belts is less than 1.0 cm. The motors for the two belts are linked and synchronize so that if one belt changes speed, the other automatically follows. Each belt is mounted on its own 6 axis force plate, used to collect ground reaction forces for use in the analysis of gait kinetics. In addition to the 6 axis force data, the belt speed and incline of the treadmill are output to the dedicated data acquisition computer. The six continuous voltage outputs of the force plates correspond to the forces and torques applied in three orthogonal directions (x, y, z). These signals, along with the speed and incline, are relayed to the data acquisition computer which samples at a rate of 1200Hz in order to convert the analog signals to digital and store them as data files. The speed and incline of the treadmill is controlled by a dedicated computer, which was monitored at all times. For the safety of the subjects, the treadmill has two large emergency stop buttons which stop the belt motors almost instantly. One of these buttons is beside the control computer and the other is mounted on the hand rail of the treadmill, within reach of the subject. Additionally, a trained safety spotter stood beside the treadmill at all times of operation to prevent subjects from tripping or falling.

Three-dimensional kinematic data was collected by 12 ProReflex Motion Capture Unit (MCU) cameras (Qualisys Medical AB, Gothenburg, Sweden). Using infrared light, the MCU cameras track the motion of retro-reflective markers, about 19mm in diameter, placed on the volunteers' skin and clothing. The 12 cameras were suspended from the ceiling around the treadmill at a 10 ft to 15 ft radius, allowing for markers on all sides of the subject to be captured in three-dimensional space. This allows for 6 degree of freedom biomechanical movement analysis for each body segment. The digit output of these cameras is synchronized with the force plate data from the treadmill.

The 3-dimensional coordinated of each reflective marker were recorded and labeled using Qualisys Track Manager (QTM) software (Qualisys Medical AB, Gothenburg, Sweden). By incorporating the body geometry of each subject with the matching marker data, these data

were then processed using Visual3D software (C-Motion Inc., Germantown, MD) to relay the reflective markers into kinematic variables for the body segments. This process results in the extraction of each subject's trunk, hip, knee, and ankle angles, as well as segment displacements, velocities, and accelerations. By analyzing the movement of the foot segment, temporal gait parameters, such as stride length, stride width, stride frequency, swing time, and double support time, were calculated.

In order to monitor metabolic costs with each condition, oxygen consumption was measured. To collect oxygen consumption (VO_2) data, a TrueMax 2400 metabolic measurement system (ParvoMedics, Salt Lake City, UT) was used at the end of the bouts of walking and running. The system monitors oxygen uptake and carbon dioxide production, which are directly linked to metabolic energy expenditure, through a snorkel-like flexible hose held to the subject's mouth, while nasal exhalation is halted by a nose clip. The system records this data, averaged over 20 second intervals, for 160 seconds. During this 160 second period, heart rate is also recorded using a Polar Vantage Heart Rate Monitor (Polar USA, Inc., Port Washington, NY). This system monitors heart rate via ECG signal collected by a chest strap and then transmitted wirelessly to a watch-like display.

4.5 Procedures

4.5.1 Orientation (one session)

Each volunteer was sized for all armor and other equipment used during testing at the start of his orientation session. After this, the volunteer was shown the testing area and introduced to the testing equipment, including the treadmill and VO_2 collection system. They were then shown how to properly secure the mouthpiece and nose clip of the VO_2 system. After this, the volunteer was asked to walk on the treadmill at 3 mph and 0% grade for a total of 4

minutes. The speed was then gradually increased to 5.5 mph, and the volunteer was asked to run for an additional 4 minutes. The subjects were then invited to rest for 10 minute.

After resting, the volunteers then put on the full armor configuration; including ACH, IBA, and extremity armor. The volunteer was then asked to repeat the walking and running while wearing the armor in order to become familiar with completing the tasks with the added weight and limitations of the armor components.

4.5.2 Data Acquisition Sessions (three sessions)

For each data acquisition session, a volunteer was tested while wearing one of the three different armor conditions **(Table 3)**. The volunteer's body mass was recorded at the start of each session. The volunteer then donned the Polar heart rate monitor chest strap and the appropriate armor and clothing for the testing session. After this, the reflective motion capture markers were attached to the volunteer's skin and clothing using athletic tape and double-sided tape (**Figure 5**). Tracking markers were placed on each volunteer's feet (over the boot), lower legs, thighs, chest, upper arms, forearms, and head (over the helmet). Markers, tape, and heart rate monitors were placed so as to cause as little discomfort and interference with normal joint motion as possible. Once markers were in place on the appropriate segments, a static calibration measurement was captured with the MCU cameras while the volunteer stood stationary on the treadmill. During this static calibration capture, the positions of joints and other important anatomical landmarks were recorded using a pointer outfitted with its own reflective markers. This collection was later used to identify the volunteer's body geometry and the anatomical position of each marker on the body segments. Though a subjects anatomical geometry does not change, a new static calibration file must be collected for session, due to variation in placement of the tracking markers between sessions.

Volunteers were asked to walk for approximately 15 minutes on the treadmill at 3 mph (1.34 m/s). This amount of time was necessary to allow for the subjects' gait kinematics and

oxygen consumption levels to reach a steady and reproducible state (Smith & Martin, 2007; Quesada et al., 2000). After 5 minutes of walking, the investigators applied the nose clip and mouthpiece to the volunteer, without halting the treadmill, and then began sampling oxygen uptake with the ParvoMedics system for 160 seconds. Once the task of walking with a rifle was completed, the rifle was taken away and the volunteer continued to walk on the level (0% grade) treadmill for an additional 5 minutes with the appropriate armor configuration being the only applied load. After this 5 minute period of walking the 20 seconds of kinematic data was collected using the MCU cameras. Ten continuous strides of data, starting with a right heel strike, were later chosen to be analyzed. Following the walking at 0% grade, the treadmill was slowly stopped and the volunteer stepped off for a brief rest period, lasting 2 minutes to 10 minutes, as needed, before moving on to another task.

After another 10 minute rest, the volunteer returned to the treadmill. The treadmill speed was then brought up to 5.5 mph (2.46 m/s). After 5 minutes, kinematic motion capture data was collected with the MCU cameras. Once the 20 second data capture was completed, the volunteer again donned the mouthpiece and nose clip so that oxygen consumption data could be collected, as was done during the walking session.

With the exception of the time when the oxygen consumption mouthpiece was in use, volunteers had access to bottled water at all times, in order to maintain hydration. Volunteers were free to stop walking or running at any time during trials if they felt any pain or excessive discomfort, at which time they would chose whether to cease testing completely, or begin the trial over again after a rest period. If a volunteer’s heart rate exceeded his age predicted maximum heart rate, testing was stopped immediately.

Figure 5. Front and rear views of test volunteer in full extremity armor condition with passive reflective motion capture markers for the static calibration capture. Tracking markers for the body segments as well as joint markers are worn in this picture. After the static calibration capture, joint markers at the ankles, knees, elbows, and wrists are removed.

4.6 Data Analysis

Once the recorded trajectories of the motion capture markers were recorded and labeled in QTM, they were exported to Visial3D, along with the static calibration file. The marker locations and anatomical landmark locations in each static calibration file were then used to build a virtual model of the body segments and joint linkage of interest: the feet, shanks, thighs, and torso (**Figure 6**). The arm motions were neglected as they have been found to have no significant impact on oxygen consumption in level gait (Chapman & Ralston, 1964; Hanada & Kerrigan, 2001). The appropriate model was then applied to the motion capture data for each

trial. With the body segments and joints defined in each motion file, an inverse kinematics algorithm was applied in order to limit noise and motion artifacts in the motion of the segments (Lu & O’Connor, 1999). The inverse kinematics tool in Visual3D analyzes the motion of all segments as a jointed system, or kinematic chain, and applies the limitations on degrees of freedom that are known for each joint. This results in kinematic trajectories that have been filtered and optimized to eliminate joint motions that would be physically impossible in health joints, such as translation in the hip joint or knee rotation in the frontal plain, based on the segment motions observed by the motion tracking system. With the body segments and joints defined, joint angles and segment displacements were then measured. A definition of the joint angles analyzed can be seen in **Figure 7**.

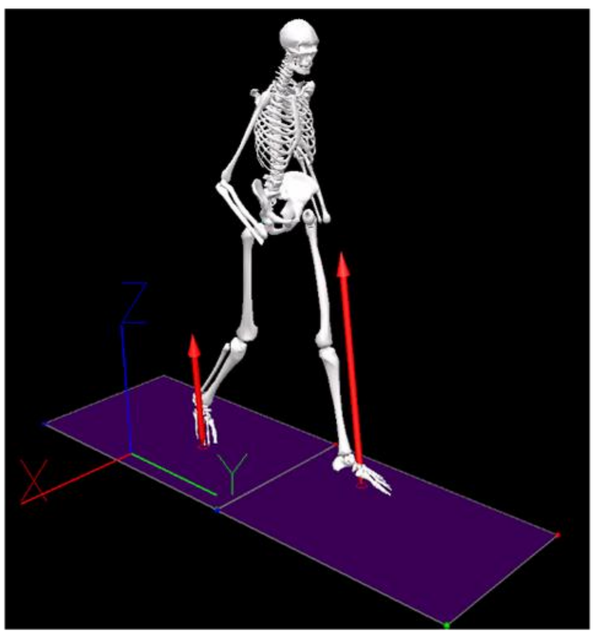

Figure 6. Volunteer body segments virtual model of walking on treadmill in Visual3D (C-Motion Inc.)

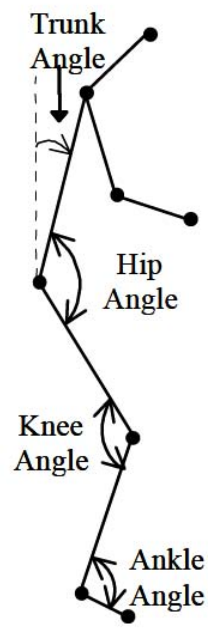

Figure 7. Definition of sagittal plane joint angles for kinematic analysis.

From the 20 seconds of kinematic data that was captured for each trial, 10 consecutive strides were chosen for analysis, based on completeness of data and proper positioning of the subject on the treadmill. The first step in analyzing gait kinematics was to label gait events, namely heel strikes and toe offs, were labeled across all signals. With these events labeled, time related measures such as stride time, double support time, cycle time, swing time, and stance time were determined, as well as event dependent measures of stride length and stride width. Each set of 10 strides included 5 strides initiated with right heel strikes and 5 with left heel strikes. The joint angles and temporal data for those 10 strides were then calculated as signals for analysis. From the calculated ankle, knee, hip, and torso angle signals, maximum and minimum joint angles in the sagittal plane were labeled. The difference between these maximum and minimum values resulted in the range of motion (ROM) of each joint in the sagittal plane. The kinematic parameters calculated for each joint were limited to the sagittal plane, as it has also been shown that kinematics in other planes suffer from poor between-day

repeatability, due to marker placement and tissue movement artifacts, which could eliminate any statistically significant findings (Kadaba et al., 1989). The sagittal plane is also the plane of most interest as it is plane in which a majority of movement in gait takes place, and as such, the most changes due to loading should occur (Martin & Nelson, 1986).

With the calculated joint ROMs and other kinematic variables derived from the motion capture data, the resulting values of each variable were averaged to produce a single mean value per variable for each trial. Because the loads carried on the body were symmetrical and the volunteers were free from injury or ailment affecting their gait, symmetry of gait was assumed for all subjects. Base on this assumption, kinematic and temporal variables were averaged across all 10 strides for each trial, rather than divided between left and right limbs. These variables were then exported for statistical analysis.

In order to evaluate the benefit of increasing the amount of armor wore, coverage area of the three armor conditions were calculated from 3-dimensional body surface scans (**Figure 8**). The 3-dimensional scans, collected in a previous study (N=10), were taken using a Cyberware WB4 whole-body surface scanner (Cyberware, Inc., Monterey, CA). This device uses low powered visible light and infrared lasers in concert with digital cameras to create a 3-dimensional map of the surface of the body. By comparing scans taken both with and without the armor conditions, the area of armor coverage was calculated using the cross section method (Hasselquist et al. 2008a). This existing data was repurposed for this study by recalculating the coverage area for the upper and lower limb segments of the extremity armor, which had previously been analyzed together, separately for each limb segment. This resulted in the difference in total coverage and percent body coverage for both the partial and the full extremity armor conditions.

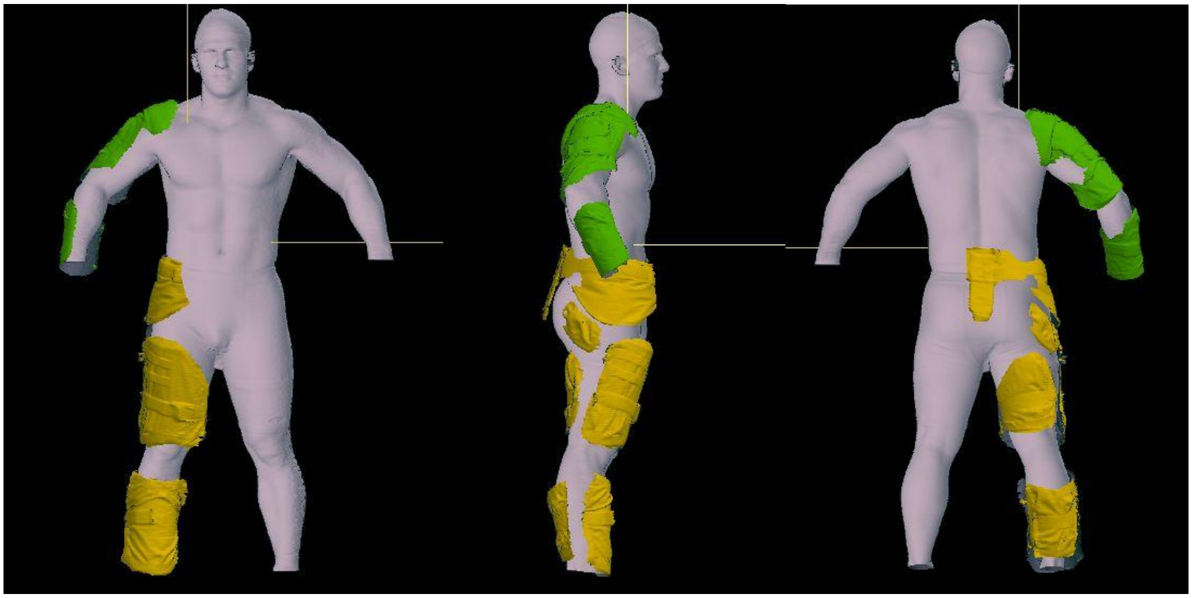

Figure 8. Front, side, and back views of 3-dimensional body scans of IDAS extremity armor on a volunteer. Note that only the right half of the IDAS armor is show in these scans. Scans do not include IBA vest or helmet.

4.7 STATISTICS

Statistical comparisons for kinematic variables were performed using SPSS 13.0 (SPSS, Inc., Chicago, IL). In order to identify deviations in kinematic variables and metabolic cost as compared to unloaded, normal gait, one-way repeated measures analysis of variance (ANOVA) was employed to compare the metabolic and kinematic variables in the no armor, partial extremity armor, and full extremity armor conditions. The ANOVA was done for walking and running conditions separately, as walking and running kinematics are known to differ substantially (Ounpuu, 2004). Statistical significance was defined as $p<0.05$. The ANOVA assumes that there is homogeneous variance in the differences between levels of the repeated measures, known as sphericity (UCLA: Academic Technology Services, 2010). A violation of this assumption can result in false positive findings of significance. The assumption of sphericity when using the ANOVA was tested in SPSS using Mauchly's sphericity test. In cases where this assumption of equal variance was violated, the Greenhouse-Geisser correction factor was applied to properly reduce the degrees of freedom of the variable, eliminating false positives.

The ANOVA also assumes a normal, or Gaussian, distribution of that data (UCLA: Academic Technology Services, 2010). This assumption was not tested. In order to test the probability of Type II error, post hoc power analyses were also completed in SPSS with each ANOVA. Power was considered to be high enough to adequately accept the null hypothesis at $P>0.80$. These results can be found in **Appendix A**.

In order to identify the statistical differences between individual armor conditions, post-hoc Bonferroni tests were completed for variables which displayed significant differences as a result of the ANOVA. A $p<0.05$ level of significance was again used in these tests. To test for significant effects that may have been missed by the conservative Bonferroni post-hoc comparisons, Paired Samples T-Tests ($p<0.05$) were also run for the data, pairing the partial extremity armor conditions with the full extremity armor conditions. No new effects, however, were observed.

CHAPTER 5: RESULTS

Of the 15 volunteers who participated, 12 completed all conditions of the kinematic testing and oxygen consumption testing, to measure metabolic cost, for walking (means- age: 22.2 yrs; height: 1.79 m; weight: 86.34 kg), while only 8 volunteers completed all testing for the running conditions (means- age: 22.4 yrs; height: 1.79 m; weight: 86.41 kg). As analyses of walking and running data sets were done separately, the data from all 12 of the subjects who completed the walking conditions were used in the statistical analysis the effects of extremity armor during walking, even though only the data for the 8 volunteers who completed all testing conditions at both speeds could be used in analyzing the effects during running.

5.1 METABOLIC COST

Wearing extremity armor during walking caused significant ($p<0.05$) increases in metabolic cost, from both partial and full extremity armor coverage conditions, as compared to walking without armor (**Table A1**). The partial coverage and full coverage armor configuration resulted in a 23% and 27% rise in oxygen consumption (metabolic cost), respectively, as seen in **Figure 9**. When metabolic cost was normalized to body mass in order to account for differences in metabolic costs between subjects, oxygen consumption per kilogram (mL/kg/min) remained significantly higher with use of extremity armor as compared to the no armor condition (**Table A2**). The partial and full extremity armor configurations caused an increase in oxygen consumption per kilogram of body mass of 18% and 23%, respectively. After normalizing for the total mass of the volunteer's body mass plus the mass of the armor, differences in oxygen consumption between the three armor conditions were no longer statistically significant (**Figure 10** and **Table A3**). No statistically significant difference in oxygen consumption, or mass normalized oxygen consumption, was found between the partial extremity armor and the full

extremity armor conditions, though a 5% rise in normalized metabolic cost when using the full extremity armor configurations as compared to the partial extremity armor configurations was observed.

The effects of wearing armor on the metabolic cost of running were similar to those on walking. Partial and full armor conditions resulted in significantly higher oxygen consumption levels, 25% and 27%, respectively, compare to walking with no armor. Likewise, oxygen consumption normalized to body mass (mL/kg/min) increased 23% due to the partial armor configurations, and 24% with use of the full armor configuration as compared to the no armor condition. When oxygen consumption was normalized to total mass, the statistical difference between the three armor conditions again dropped out. As in walking, the upward trend in oxygen consumption and mass normalized oxygen consumption from the partial armor configuration to the full armor configuration was not statistically significant.

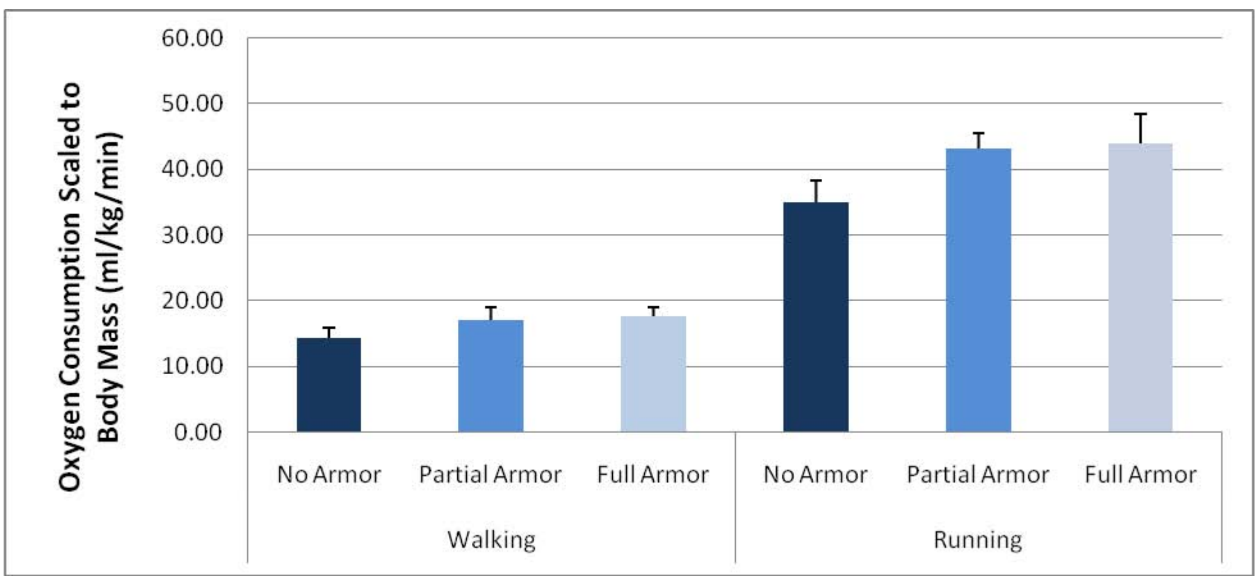

Figure 9. Effect of extremity armor coverage on oxygen consumption per kilogram of body mass during walking and running. Means are displayed, with error bars indicating standard deviation. No Armor = no extremity armor or IBA vest; Partial Armor = partial extremity armor configuration; Full Armor = full extremity armor configuration.

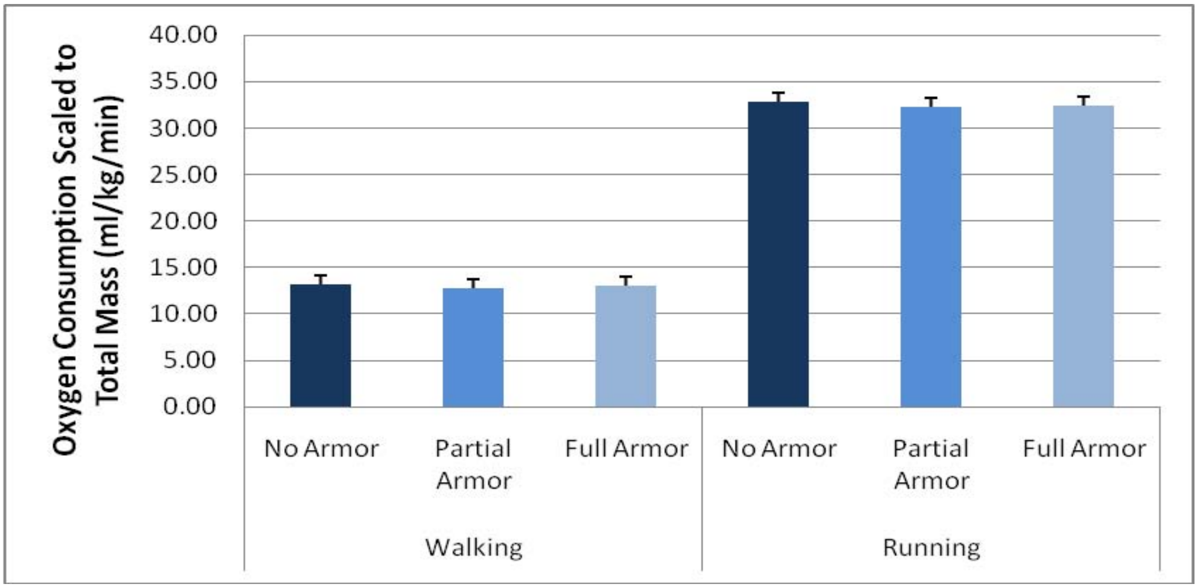

Figure 10. Effect of extremity armor coverage on oxygen consumption per kilogram of total mass (body mass + load mass) during walking and running. Means are displayed, with error bars indicating standard deviation. No Armor = no extremity armor or IBA vest; Partial Armor = partial extremity armor configuration; Full Armor = full extremity armor configuration.

5.2 KINEMATICS

5.2.1 Spatial and Temporal Parameters

Very little effect of armor level was found in the spatial and temporal gait parameters. As can be seen in **Tables 4** and **5**, step length, defined as the distance in the direction of walking between the heel strike of one foot to the next heel strike of the contralateral foot, and stride width, calculated as the perpendicular distance between said heel strikes, showed no significant differences between levels of armor coverage in walking or running. The time between contralateral heel strikes, which is labeled step time, did not show any significant changes between conditions either, nor did stance time or swing time change significantly. Cycle time, which is the sum of two consecutive step times, showed an increase with use of extremity armor, though this trend was not significant. The only temporal variable that showed a statistical significant effect of armor level was double limb support time, the period when both feet contact

the ground, which increased about 5% due to both partial and full armor configurations, as compared to the double limb support time in walking with no armor. Swing time in running also approached significance (p= 0.067) between the no armor condition and the other two conditions.

Table 4. Effects of extremity armor coverage on temporal gait parameters in walking and running. Asterisks indicate variables in which the No Armor condition differed significantly (p > 0.05) from the Partial and Full Armor conditions.

Temporal Parameters							
Means (SD)	Cycle Time (sec)	Stance Time (sec)	Step Time (sec)	Swing Time (sec)	Double Limb Support Time (sec) *	Initial Double Limb Support (sec) *	Terminal Double Limb Support (sec) *
Walking:							
No Armor	1.077 (0.037)	0.696 (0.024)	0.539 (0.019)	0.382 (0.016)	0.314 (0.018)	0.157 (0.011)	0.157 (0.010)
Partial Armor	1.084 (0.037)	0.707 (0.023)	0.542 (0.018)	0.377 (0.015)	0.330 (0.009)	0.166 (0.009)	0.164 (0.006)
Full Armor	1.080 (0.031)	0.706 (0.019)	0.540 (0.015)	0.374 (0.012)	0.332 (0.011)	0.165 (0.008)	0.166 (0.008)
Running:							
No Armor	0.760 (0.031)	0.423 (0.017)	0.380 (0.016)	0.337 (0.018)			
Partial Armor	0.747 (0.029)	0.422 (0.019)	0.373 (0.014)	0.325 (0.015)			
Full Armor	0.746 (0.025)	0.423 (0.015)	0.373 (0.013)	0.324 (0.015)			

Table 5. Effects of extremity armor coverage on spatial and temporal gait parameters in walking and running. No significant differences (p > 0.05) were found.

Spatial and Temporal Parameters						
Means (SD)	Step Length (m)	Stride Length (m)	Stride Width (m)	Strides Per Minute	Steps Per Minute	Statures Per Second
Walking:						
No Armor	0.727 (0.027)	1.453 (0.054)	0.153 (0.034)	55.757 (1.887)	111.494 (3.774)	0.759 (0.031)
Partial Armor	0.762 (0.127)	1.524 (0.253)	0.154 (0.023)	55.395 (1.888)	110.803 (3.778)	0.787 (0.129)
Full Armor	0.722 (0.022)	1.444 (0.044)	0.150 (0.028)	55.605 (1.590)	111.211 (3.126)	0.752 (0.026)
Running:						
No Armor	0.987 (0.194)	1.972 (0.388)	0.100 (0.043)	79.066 (3.160)	158.207 (6.432)	1.460 (0.255)
Partial Armor	0.966 (0.177)	1.933 (0.351)	0.094 (0.034)	80.450 (3.197)	160.944 (6.380)	1.452 (0.258)
Full Armor	0.914 (0.030)	1.828 (0.060)	0.095 (0.033)	80.482 (2.805)	160.981 (5.625)	1.382 (0.048)

5.2.2 Sagittal Plane Joint Angles

Analysis of joint ranges of motion (ROM) during walking displayed an effect of extremity armor on the ankle, hip, and knee. Armor resulted in a statistically significant reduction in ankle ROM, while knee and hip ROM increased significantly (**Table A4**). As in oxygen consumption data, however, there were no statistical differences in ranges of motion of these joints between the partial extremity armor and full extremity armor conditions. The mean joint ranges of motion displayed a trend in which the full extremity armor configurations resulted in a less severe deviation from normal joint ROMs than the partial extremity armor configurations (**Figure 11**). The change in ROM of the ankle was the result of a decrease in maximal plantar flexion per step, as can be seen in **Table 6**. In comparison to the partial extremity armor condition, the mean maximal plantar flexion angle was significantly higher with the full armor condition. There

was also a smaller, but still statistically significant increase in maximal dorsiflexion per step associated with the use of any extremity armor. At the knee, the increase in ROM was caused by a rise in maximum knee flexion due to the load of the extremity armor. An increase in maximum hip flexion was responsible for the change in hip ROM with the addition of extremity armor.

In running, an increase in hip flexion and extension when extremity armor was worn resulted in an increased ROM at the joint, as compared to the no armor condition (**Figure 12**). This increase in ROM was statistically equivalent whether the partial armor configuration or the full armor configuration was donned. Ankle kinematics in running were also affected by level of armor coverage, with an increase in dorsiflexion and a decrease in plantar flexion. The decrease in plantar flexion was significantly less with the full extremity armor configuration, as compared to the partial configuration. Use of extremity armor also caused a decrease in maximum knee extension in running, as can be in **Table 7**, though this decrease was not enough to significantly affect ROM of the knee. Range of motion of the trunk was also found to be significantly increased in running with use of extremity armor.

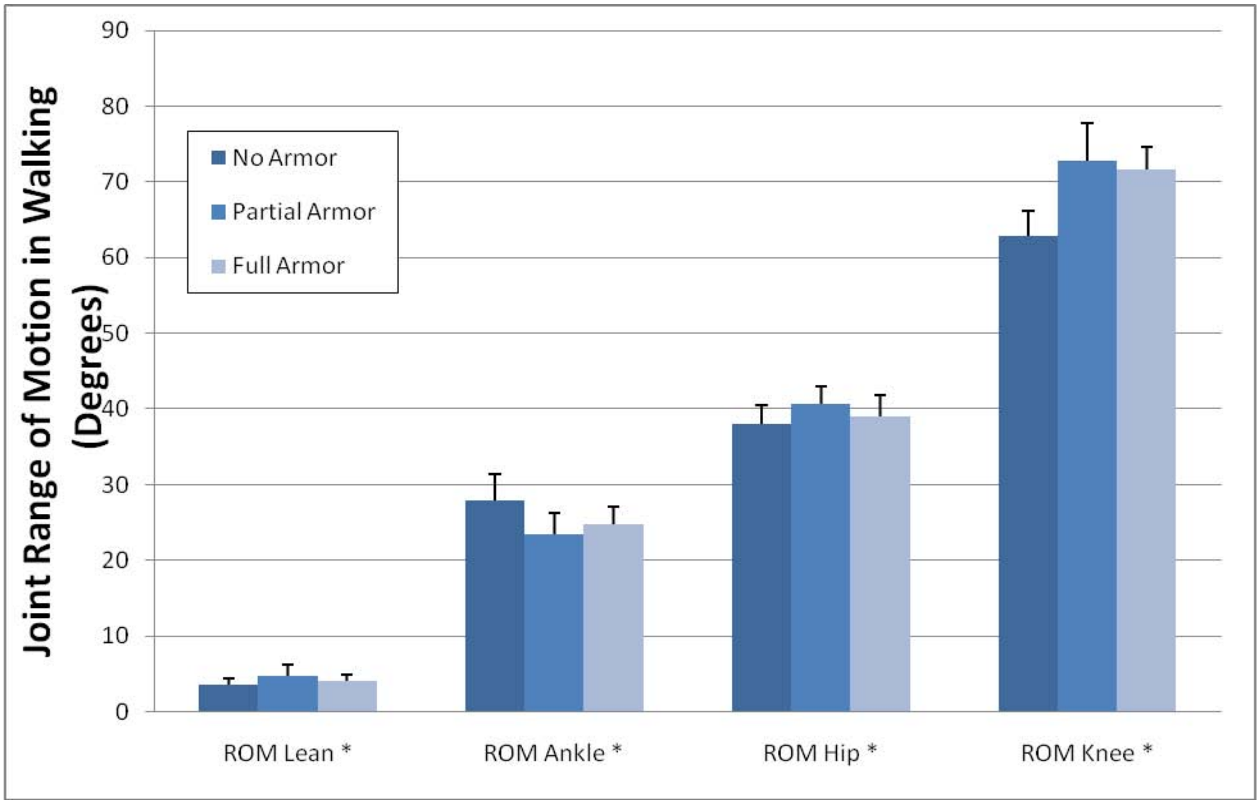

Figure 11. Sagittal plane range of motion of the joints during walking. Means are displayed, with error bars indicating standard deviation. Asterisks indicate variables in which the No Armor condition differed significantly ($p > 0.05$) from the Partial and Full Armor conditions. No Armor = no extremity armor or IBA vest; Partial Armor = partial extremity armor configuration; Full Armor = full extremity armor configuration. Ankle range of motion (ROM) was reduced by wearing either extremity armor configuration, while hip and knee ROM were increased. No significant differences were found between Partial and Full Armor conditions.

Table 6. Mean sagittal plane joint excursions per step during walking. Asterisks indicate variables in which the No Armor condition differed significantly ($p > 0.05$) from the Partial and Full Armor conditions. No Armor = no extremity armor or IBA vest; Partial Armor = partial extremity armor configuration; Full Armor = full extremity armor configuration. Dorsiflexion and knee flexion were increased when armor was worn, while plantar flexion decreased. No significant differences were found between Partial and Full Armor conditions.

Maximum Excursions During Walking			
Means (SD)	No Armor	Partial Armor	Full Armor
Max Lean Angle	1.94 (11.98)	11.84 (3.88)	12.06 (3.07)
Max Ankle Dorsiflexion *	6.15 (3.96)	12.64 (4.89)	10.55 (4.22)
Max Hip Flexion	35.42 (6.60)	38.02 (4.74)	37.47 (5.69)
Max Knee Flexion *	60.25 (4.46)	71.01 (6.18)	69.99 (6.09)
Min Lean Angle	1.64 (12.32)	7.12 (4.20)	8.05 (3.03)
Max Ankle Plantar Flexion *	21.81 (5.99)	10.74 (3.39)	14.15 (4.30)
Max Hip Extension	2.62 (7.23)	2.66 (4.19)	1.52 (7.00)
Max Knee Extension	2.52 (4.44)	1.74 (3.02)	1.60 (5.73)

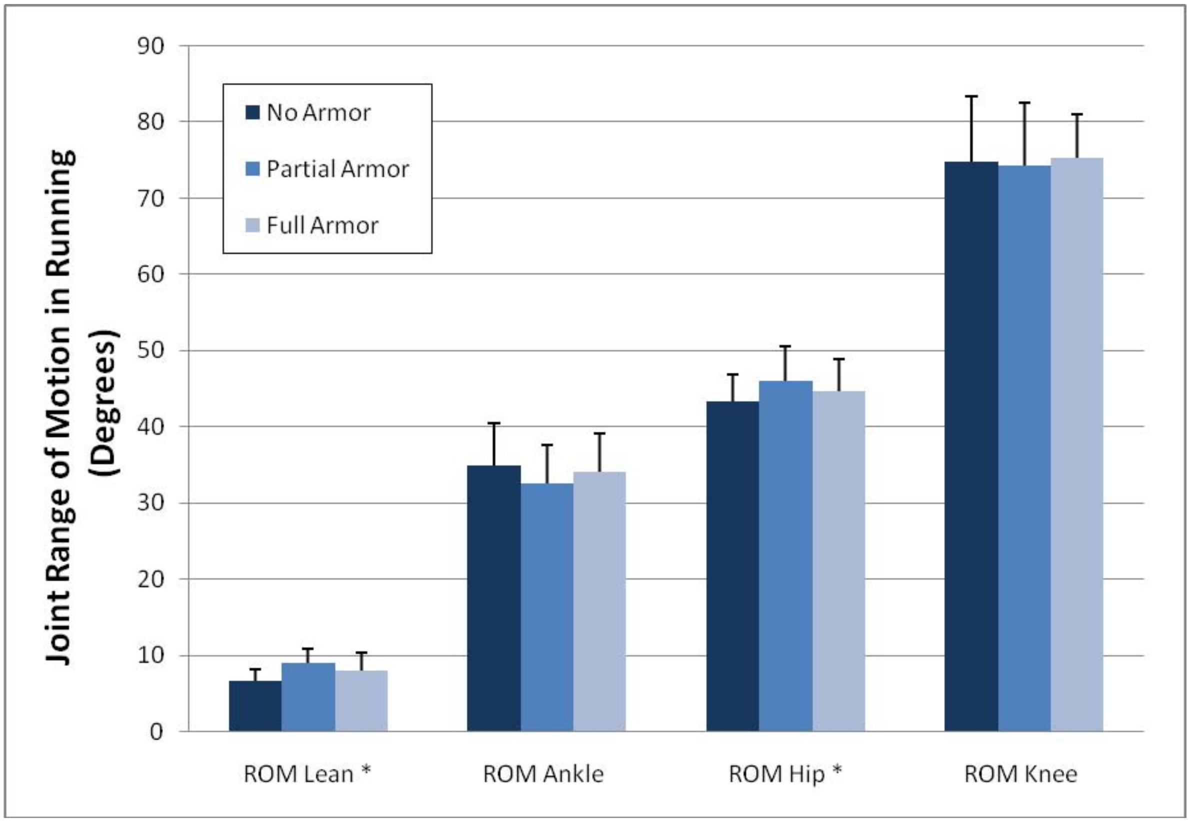

Figure 12. Sagittal plane range of motion of the joints during running. Means are displayed, with error bars indicating standard deviation. Asterisks indicate variables in which the No Armor condition differed significantly ($p > 0.05$) from the Partial and Full Armor conditions. No Armor = no extremity armor or IBA vest; Partial Armor = partial extremity armor configuration; Full Armor = full extremity armor configuration. Hip ROM and Lean ROM increased when using the extremity armor in either configurations, but no significant differences were found between Partial and Full armor conditions.

Table 7. Mean sagittal plane joint excursions per step during running. Asterisks indicate variables in which the No Armor condition differed significantly ($p > 0.05$) from the Partial and Full Armor conditions. Dorsiflexion, hip flexion, knee flexion, and knee extension were increased when armor was worn, while plantar flexion and hip extension decreased. No significant differences were found between Partial and Full armor conditions.

Maximum Excursions During Running			
Mean (SD)	No Armor	Partial Armor	Full Armor
Max Lean Angle	15.11 (8.32)	9.94 (5.32)	12.27 (3.65)
Max Ankle Dorsiflexion *	13.72 (3.03)	20.26 (5.33)	18.38 (3.88)
Max Hip Flexion *	39.01 (4.32)	48.94 (8.17)	47.32 (4.89)
Max Knee Flexion *	81.20 (7.37)	86.66 (6.60)	85.81 (4.38)
Min Lean Angle	21.76 (8.97)	0.86 (5.48)	4.23 (3.82)
Max Ankle Plantar Flexion *	21.27 (5.62)	12.01 (5.35)	15.64 (5.87)
Max Hip Extension *	4.24 (4.77)	2.84 (6.79)	2.67 (8.08)
Max Knee Extension *	6.44 (4.79)	12.39 (5.91)	10.59 (6.97)

5.3 AREA OF COVERAGE

The 3-dimensional scanning (**Figure 13**) showed that the full extremity armor coverage configuration, including the IBA armor vest covering the torso, covered an approximate average of 0.717 m^2 of the soldiers' body, which was approximately 40.84% of the mean total body surface area of 175.58 m^2 (standard deviation: 13.12 m^2) of the volunteers. Removal of the forearm and lower leg portions of the extremity armor, leaving the partial extremity armor configuration, resulted in the body surface coverage to diminish to approximately 23.41% of body surface area of the volunteers, which is approximately 0.411 m^2. This was an average difference of approximately 0.089 m^2 of body coverage area. The IBA vest alone accounted for 0.411 m^2 (0.03 m^2), or 23.41% of the mean total body surface area (**Table 8**).

Table 8. Mean area of body coverage per extremity armor component and configuration.

Mean (SD)	Area of Coverage (m^2)		Percentage of Body Surface Covered
Body Surface Area	175.5	(13.12)	-
IBA Vest	0.411	(0.033)	23.41%
Partial Configuration	0.628	(0.049)	35.77%
Full Configuration	0.717	(0.052)	40.84%

Figure 13. An example of calculated 3-dimensional area of coverage (red) for full coverage configuration of IDAS extremity armor.

CHAPTER 6: DISCUSSION

6.1 METABOLIC COST

The 18 to 23% increase in metabolic cost per kilogram of body mass during walking (1.34 m/s) with extremity armor observed in this study are similar to the results of Hasselquist et al. (2008a), in which three distinct extremity armor designs of similar weight and distribution to the full extremity armor configuration tested here yielded 22 to 26% increases in metabolic cost per kilogram. The previously reported 7% increase in metabolic cost per kilogram due to extremity armor use during running (2.26 m/s) (Hasselquist et al., 2008a), however, was noticeably lower than the 23 to 24% increase in metabolic cost per kilogram found in this study. The primary reason for the differences in the metabolic costs of running with armor was most likely the difference in masses between the IBA vest used in this study and the armor vest used in the Hasselquist et al. study. The IBA vest used in this study was outfitted to match battlefield configurations, which include loaded ammunition and grenade pouches, bringing the mass of the vest to roughly twice the 8.7 kg weight of the armor vest used by Hasselquist et al. In the current study, the full extremity armor configuration plus rifle was approximately 34.3% body mass and the partial extremity armor configuration plus rifle was approximately 32% body mass, as opposed to the 26% body mass used in the previous extremity armor research. This increased load weight would have a more significant detrimental effect at higher speeds (Pandolf et al., 1977; Giovani & Goldman, 1971). This may explain the similarity between studies in metabolic costs found walking and simultaneous differences between the two studies in metabolic costs observed during running. A second factor which may have accounted for a small percentage of the increase in volunteers' metabolic efficiency in load carriage of the previous study was a higher level of previous experience in walking and running with a military load. Schiffman et al previously found that familiarization with carrying backpack loads could

reduce metabolic cost in soldier volunteers who carried novel loads (Schiffman et al., 2008). In the Hasselquist et al. study, all but one volunteer were trained as infantry soldiers (Military Occupational Specialty 11B) in Advance Individual Training (AIT). In contrast, only five volunteers from the current study received infantry training. Infantry soldiers spend significantly more time training, both walking and running, with load carriage, including ballistic armor such as the IBA vest. This is due to the fact that infantry soldiers are more likely to carry such a load on the battlefield, and must be physically prepared to do so. It is possible that the familiarization process observed by Schiffman et al. continued beyond the two days tested, and that carrying a backpack load for even greater periods of time, as in AIT, continues to improve efficiency of walking and running with a load. The previous research on familiarization with loads (Schiffman et al., 2008), however, focused on very novel backpack loads with extreme moments of inertia, unlike anything volunteers had been exposed to before. This differs significantly from the comparatively compact IBA vests with combat load used in this study, in which the mass was close to the body's natural center of mass.

When comparing between levels of extremity armor coverage, i.e. the partial coverage condition versus the full coverage condition, though there were increases of 4.1% and 1.8% in metabolic cost per kilogram of body mass for walking and running, respectively, these changes did not approach statistical significance. This was contrary to the hypothesis that the additional 2 kg weight of extremity armor on the forearms and shanks would yield significantly higher metabolic costs due to the distal placement of the mass on the limbs, particularly the distal components of the legs, which account for 1.5 kg (**Table 1**). The null hypothesis that there is no effect of the full extremity armor configuration on metabolic cost as compared to the partial extremity armor configuration in walking is validated due to the high observed power of the data ($P>0.80$), indicating that Type II Error is unlikely. Per power analysis, the lack of effect of extremity armor on metabolic cost is 85.0% likely to occur again if the study were repeated. In

running, however, the observed power was too low to be conclusive, indicating a 11.7% chance of the observed relationship reoccurring.

Previous research in shank loading during walking has indicated a statistically significant increase of 8% in metabolic cost of walking found when masses of 2 to 2.8 kg per shank are applied (Browning et al., 2007; Royer & Martin, 2005). The 0.75 kg mass of each shank components of the extremity armor system did not reach this level of loading and did not approach significance. In loading of the upper extremities, the arm coverage section of the extremity armor system did not meet the threshold of 2.27 kg at which hand-held weights had been found to cause a significant effect on metabolic cost (Owens et al., 1989). The elimination of an effect of extremity armor on metabolic cost when normalized to total mass of the user and armor system is also in agreement with the findings of the extremity armor testing of Hasselquist et al. (2008a). It is hypothesized that mass of the distal components of the extremity armor which cover the shanks and lower arms was below the threshold needed to produce statistically significant differences in metabolic cost of walking or running at the position which it was attached. An additional factor which may contribute to the differences in both previous and current studies of extremity armor verses other extremity loading research is the distribution of the load. In the use of extremity armor, the loading of the limb segments is evenly distributed across the anterior and posterior surfaces of the limb segments, therefore, resulting it little change to the position of the center of mass of the limb segment. In the testing of Royer and Martin (2005), a pouch filled with lead shot was used in order to load the shank and thigh. Though distribution of the mass used by Royer and Martin around the limb segment was not reported, it is possible that the position of the load and resulting change in center of mass of the limb-load system increased the strain on the body to stabilize the limb during walking. This instability may have induced the greater changes to gait kinematics observed, as compared to the studies of extremity armor.

After normalizing the metabolic costs of walking and running in each condition to the total mass of the volunteer plus the mass of the armor, no significant differences in metabolic cost were found between the three levels of armor coverage (**Figure 9**). This indicated that mass of the extremity armor load alone, not the locations of placement of the armor on the extremities or the design characteristics of the armor, was responsible for the rise in metabolic costs (Goldman & Iampietro, 1962; Soule & Goldman, 1969). This is not, however, to say that the same mass would elicit the same increase in metabolic cost if applied to the torso. In order to validate such a claim, the metabolic effects of torso masses equal to the masses of the loading configurations tested here would have to be tested. Previous research has indicated that a significant increase in metabolic cost of walking due to torso loading is not observed until the mass of the load is equal to or above 10% body mass (Hong et al., 2000; Robertson et al., 1982). The 6.5 kg extremity armor alone did not reach this level, but the partial armor (24.9 kg) and full armor (26.9 kg) configurations tested in this study did, as they included the IBA vest, helmet, and boots. It is also important to note that scaling the metabolic cost by total mass caused the statistical power of the data to drop below the accepted 0.80, as seen in **Table A5**, indicating a high probability of Type II Error. This means that it is possible that the lack of significant difference between these conditions was a false negative, and that further testing may need to take place in order for the lack of mass placement effect on metabolic cost to be truly conclusive.

The low weight of the distal components and the even distribution of the total mass of the armor systems across the body, which likely did not disturb the body's natural center of mass location, may have played a part in eliminating any effect of mass placement on the limbs. If the center of mass of the body remained unchanged due to the similar masses of the arm armor components and the leg components, the effect of the load on the metabolic costs of locomotion would be less than if asymmetric loading had manipulated the center of mass of the system (Legg & Mahanty, 1985; Lloyd & Cooke 2000; Coombes & Kingswell, 2005). This theory

could be tested in the future by examining the effects of the arm components and the leg components from each other. Testing the metabolic cost of walking and running with the arms alone may prove to result in an insignificant change, as the mass may not be enough to affect the metabolic cost.

6.2 Kinematics

Fewer changes in the temporal and spatial kinematics due to extremity armor were observed in this study than anticipated. It should be noted that the observed power was too low (**Table A6** and **A7**) to negate Type II Error for all temporal variables found to be unaffected by armor load, with the exception of swing time in running. While no significant differences were found in these parameters between the partial extremity armor and full extremity armor conditions, trends in the data did exist. Due to the low observed power of these variables, such trends may have proven to be significant had data for a larger sample population been available.

The 5% increase in double support time due to walking with extremity armor was the only finding of the temporal or spatial parameters to be statistically significant. Double support time has been suggested to reflect stability of gait, with increased contact with the ground being needed to feel secure and perchance reduce the likelihood of a slip or fall (Yang & Hu, 2009). The increase in double support time for both conditions in which armor was worn, as compared to the no armor condition, resembles the increases in double support time found in the carriage of torso loads of 20% body mass or greater (Kinoshita, 1985; Martin & Nelson, 1986). Only one study, however, has reported any changes to double support time with extremity load. Hasselquist et al. (2008a) found significant increases in double support time during walking with armor versus walking with no armor. They did not observe any significant differences in double support time with use of an armor vest alone as compared to use of an armor vest with

extremity armor systems. In maintaining a constant total load while manipulating the distribution of the mass from completely torso borne to 50% on the lower extremities, Browning et al. (2007) found that while the torso load caused a 10% increase in double support time, no change was found when part of the load mass was applied to the shanks or feet. This implies that the large mass of the armor vest (8.7 kg) may contribute to the increased double support in walking found both by Hasselquist et al. and the current study.

Changes in swing time and stance time were expected based on previous research (Martin & Nelson, 1986; Royer & Martin, 2005; Browning et al., 2007; Hasselquist et al., 2008; Martin, 1985). Martin and Nelson found that swing time decreased as torso borne loads increased up to 40 kg. This reduction in swing time was necessary to allow for the increase in double support time, as walking speed was maintained constant by a treadmill. Royer and Martin found that applying loads of 2 to 2.8 kg to the shanks increased swing time by 2.3%. Browning et al. found even greater alterations in swing time with larger loads applied more distally at the feet. Loads of 2 and 4 kg per foot increased swing time by 9 and10%, respectively (Browning et al., 2007). This increase in swing time can be explained by the passive pendulum model for the swing limb. As the moment of inertia of the swing limb was increased by the distal mass, the resonant frequency of oscillation of the pendulum changed (Royer & Martin, 2005; Holt et al., 1990). It was theorized that allowing the limb to swing at the resonant frequency optimizes the energetic of walking, as altering the swing time away from the natural swing time would increase metabolic cost (Royer & Martin, 2005; Browning et al., 2007; Holt et al., 1990). The previous research in extremity armor, though, found that compared to no armor, one of the three extremity armor systems tested resulted in shorter swing times, whereas no significant differences were found with the other two extremity armor systems or the armor vest condition (Hasselquist et al., 2008a). The lack of change in these gait variables observed in this study may also be due in part to the more even distribution of the load on the limb in extremity armor use, as compared to previous research on limb loading. Though not statistically significant,

changes in swing and stance time were observed in the current study. Compared to the no armor condition, the extremity armor conditions showed 1.5% increases in stance time during walking. Stance time in walking was reduced by 1% and 2% by partial and full extremity armor condition, respectively. In running, swing time was found to reduce by over 3.5% in extremity armor conditions. This is greater than the 1% reduction in running found by Hasselquist et al., but still did not prove to be significant.

Though not statistically significant, stride length was found to increase approximately 5% on average with use of the partial extremity armor configuration in walking, as compared to the no armor condition. It is unclear whether this increase, which translated to about 7 cm, would be too small to create appreciable changes in gait economy and metabolic cost. With use of the full extremity armor configurations, however, no change in stride length was observed as compared to the no armor condition. This may be explained by the combination of torso loading and extremity loading which occurred in extremity armor conditions. Previous research regarding torso load carriage found that increasing load mass reduces stride length, accompanied by increases in stride rate to compensate when walking speed is held constant (Martin & Nelson, 1985; LaFiandra et al., 2003). Torso loads, specifically backpacks, were hypothesized to generate reduced stride length and increased stride frequency as a result of decreased pelvic rotation due to the loading (LaFiandra et al., 2003). Lower limb loading was found to have the converse effect; with increases in stride length and decreases in stride frequency being reported for shank and foot loads up to 4.4 kg (Royer & Martin, 2005; Browning et al., 2007; Holt et al., 1990). This reduction in stride frequency is likely the result of changes in the pendulum motion of the swing leg resulting from increased moment of inertia of the limb, as swing time was, with an increase in stride length being needed to compensate at fixed speeds (Royer & Martin, 2005; Browning et al., 2007). Based on these previous findings in lower leg loading, it was expected that the distal limb loading of the full extremity armor would further increase stride length and swing time as compared to partial armor, yet, this was not observed. Similar to the current

study, Hasselquist et al. (2008a), found no significant differences in swing time in comparing extremity armor to an armor vest alone. Since the effect of extremity armor on metabolic cost was found to be primarily a result of the mass of the armor configurations rather than the distribution of the extremity armor on the legs, it can be speculated that the effect of the distal limb loading may have been negated by the increased stride frequency found in torso loading. While altering the period of oscillation of the swing limb away from resonant frequency should have resulted in an increased metabolic cost when ambulating in the full extremity armor configuration, no such increase in metabolic cost was observed.

While Hasselquist et al. (2008a) found an increase in stride width in two out of three extremity armor conditions, as compared to a no armor condition, the extremity armor system in the current study exhibited no impact on stride width. An increase in stride width might be expected to result from the thickness of material between the thighs. Had increases in stride width been present with extremity armor use, it would have indicated that changes in gait kinematics may have been due to the extremity armor's volume, rather than the masses and moments of inertia of the components. The lack of change in stride width when wearing the IDAS extremity armor is not surprising, as there is no ballistic armor on the inner thighs, only very thin fabric material no thick than an average pair of pants.

While changes in joint kinematics due to load carriage of backpacks and other torso loads have been reported on in great depth (Kinoshita, 1985; Quesada et al., 2000; Attwells et al., 2006; Browning et al., 2007; Harman et al., 2000; LaFiandra et al., 2003), little is mentioned about these variables in investigations regarding extremity loading. In this study, joint kinematics proved to be more useful variables for measuring the effects of extremity armor on gait than the temporal and spatial parameters. Significant increases in knee and hip ROM with the additional loading of extremity armor, as compared to the no armor condition, compares favorably to the findings of previous studies in load carriage of backpack load (Kinoshita, 1985; Quesada et al., 2000; Attwells et al., 2006). The increased knee flexion at heel strike due to loading and

resulting increase in ankle dorsiflexion are seen to be a result of the leg absorbing the increased impact forces of load, while the increased knee extension and plantar flexion at toe off were necessary to propel the added mass of the load forward with the body (Kinoshita, 1985; Attwells et al., 2006; Harman et al., 2000). Loading of the foot during walking was also found to increase hip, knee, and ankle extension (Browning et al., 2007).

Contradictory to this previous work, however, the extremity armor conditions in the current study were found to decrease plantar flexion at the ankle. While this reduction in plantar flexion could be explained in the full extremity armor configuration as a result of the shank armor component interacting with the combat boot to limit the ankle ROM, this is unlikely due to the fact that the partial extremity armor condition, which did not include the shank components, showed an even greater reduction in plantar flexion, as compared to the no armor condition. Since few previous studies of shank and/or thigh loading reported on joint kinematics, and those that do report no change in leg kinematics (Browning et al., 2007), it is unclear what interaction produced the decrease in plantar flexion. One possible explanation for this decreased plantar flexion is the anterior load of the IBA vest. As stated above, the IBA vest used in this study included a simulated battlefield load of mock ammunition and grenades, which are placed on the front of the IBA vest. Carriage of this anterior load may have caused the volunteers to feel unstable at toe off, resulting in a reduction in push off from the ankle for propulsion. This would then also explain the simultaneous increase in knee extension, which could compensate for lost ankle propulsion. This hypothesis could be tested by analyzing the kinetic data collected during these trials, to assess changes in propulsive forces in the sagittal plane at toe off.

Increases in hip ROM during walking have also been previously reported as a function of both backpack load carriage (Attwells et al., 2006; LaFiandra et al., 2003) as well as foot loading (Browning et al., 2007). These increases hip ROM were found to result from rises in extension at toe off, as well as increases in flexion at heel strike (Attwells et al., 2006; LaFiandra et al., 2003; Browning et al., 2007). LaFiandra et al. (2003) confirmed that increases in hip excursion

were needed to maintain stride length with backpack loading as pelvic rotation and, consequently, the contribution of hip excursion to stride length was reduced.

One of the most interesting unanticipated findings of this study was that when the lower arm and shank extremity armor components were added, going from the partial extremity armor condition to the full extremity armor condition, kinematic data consistently trended back toward normal, unloaded joint kinematics in both walking and running. As can be seen in **Figures 11** and **12,** this trend was true for all ROM variables, a majority of maximum joint excursions (**Table 6 and 7**), and many temporal variables (**Tables 4 and 5**). Some of the observed returns toward normal kinematics may be due to the contradicting effects of torso loading versus limb loading, as was discussed with stride length and swing time (Martin & Nelson, 1986; Royer & Martin, 2005; Browning et al., 2007; Hasselquist et al., 2008a; Kinoshita, 1985; Attwells et al., 2006; Harman et al., 2000). Though these changes in kinematics due to distal limb loading were not statistically significant in the current study, the trend across variables may indicate that larger loads applied to the distal limbs could evoke significant changes, possibly even reverting to a point of no significant difference from unloaded joint kinematics. More in depth characterizations of the confounding effects of torso loading with extremity loading could further explain the mechanism responsible for these changes.

As was found in the metabolic cost data, when joint kinematics data for the partial and full extremity armor conditions were considered separately from the no armor condition, the observed statistical power was found to be to low (**Table A10** and **A11**) to be considered free of Type II Error. Because of this low power, the possibility that the statistical analyses are reporting a false negative must be considered.

6.3 LIMITATIONS

One of the limitations of this study was the lack of a condition with the IBA vest alone, without any extremity armor. While the ideal design of this study would be to compare the two levels of extremity armor coverage to use of the IBA torso armor as well as a no armor condition, this was not an option due to the post hoc nature of this study and its use of previously collected data. It is reasonable to compare the two present extremity armor conditions to a condition with no armor vest, as the findings of Hasselquist et al. (2008a) had concluded previously that the armor vest alone used in their study had no statistically significant effect on oxygen consumption when compared to a completely unloaded condition, in both walking and running. With regard to kinematics, the armor vest used by Hasselquist et al. was only found to produce changes in double support time, as compared to a no armor condition, which increased by about 1% of total stride time. The IBA vest used in this study was of greater total mass than that used by Hasselquist et al. due to the additional equipment mounted to it. The loading experienced by the volunteers in this study included a combination of torso loading, due to the IBA vest loaded to simulate battlefield conditions, and extremity loading, due to the extremity armor system.

The lack of statistical power in the data of the two conditions in which armor was worn is the greatest limitation of this study. As mentioned above, the post hoc nature of this study prevented the data collection from taking on the ideal design for this study. Had the data collection been specifically for this study, a larger sample population could have been used in order to increase the statistical power of the results. The low observed power does not, however, negate the results found in this study, but rather indicates that great care must be taken when interpreting these results and applying them to a greater population.

6.4 General Discussion

The finding that the significant differences between the three levels of armor coverage, including the no armor condition, disappeared when the metabolic costs of walking and running in each was normalized to total mass indicates that the changes in metabolic cost are due to the mass of the extremity armor, rather than the placement or design of the specific armor tested. Changes observed in joint kinematics due to the loading of the extremity armor conditions support this hypothesis, as they generally resemble those adjustments seen as a result of torso loading, rather than extremity loading (Kinoshita, 1985; Quesada et al., 2000; Attwells et al., 2006; Browning et al., 2007; Harman et al., 2000; LaFiandra et al., 2003). The changes in gait kinematics indicate that the increase in metabolic cost observed was primarily due to the increased muscle activity during stance phase, as is seen with increased body mass (Griffin et al., 2003), whereas extremity loading has been found to increase muscle activity more so during swing phase (Browning et al., 2007). The leg in stance phase is responsible for braking and propelling the body, as well as acting as a tensile damper to reduce impact on the body during locomotion (Griffin et al., 2003). As load carried or body mass are increased, the volume of active muscle required to generate force on the ground increases (Griffin et al., 2003). Approximately half of the metabolic cost of normal walking is attributed to the muscle activity of the stance leg producing the forward propulsive forces needed to maintain locomotion (Gottschall & Kram, 2003). Therefore, it is hypothesized that a significant increase in the activity of the muscles used for forward propulsion and body support, such as the gastrocnemius and soleus (Gottschall & Kram, 2003; McGowan et al., 2008), are likely associated or a primary driver of the increased metabolic costs found with use of extremity armor.

6.4 IMPLICATIONS

Though the observed increases in metabolic cost resulting from extremity armor use can be explained as resulting from the additional mass of the armor, with no significant effect due to the distribution of the mass, there is still a significant increase in metabolic cost, which has practical implications. This information has very important implications to soldiers in the field. The increased energy cost as well as the changes in gait kinematics necessary to control the load when using the extremity armor rather than the IBA vest alone may make it undesirable to wear on missions than require long durations of walking and/or running, as the increased physiological strain could result in an earlier onset of fatigue and negatively impact the warfighter's physical performance. These negative effects on performance may take the form of a reduced pace in walking and running, a need for more frequent rest stops, or an increase in effort needed to execute a physical task (Hasselquist et al., 2008a). When combined with the results of Hasselquist et al. (2008a), this study indicates that energy cost requirements should be a significant contributor to deciding when extremity armor should be fielded in addition to the contribution it makes to increased ballistic protection. In finding significant changes to joint ranges of motion due to extremity armor use, this study also shows that the effects of extremity armor on joint kinematics should also be investigated and characterized prior to fielding such new systems.

The addition of the IDAS extremity armor system in the partial armor configuration increased armor area of coverage by 12.3% over the IBA vest. The full configuration of the extremity armor system increased coverage by 17.4% over the IBA vest, and 5.1% over the partial configuration. Since no significant difference was found between the metabolic costs and kinematics of wearing the partial or full extremity armor configuration, the improved body coverage of the full armor configuration should be used if the primary concern is energy expenditure during locomotion, and the ballistic protection of the IBA vest alone is deemed

insufficient. Based on the results of this study, soldiers should be notified there are no benefits in removing the forearm and shank components of the IDAS armor when when walking or running. Thus, the full configuration should be used when wearing the IDAS unless the distal components are found to inhibit some other relevant physical task.

CHAPTER 7: FUTURE WORK

The current study researched the effects of a specific extremity armor system, rather than investigating the basic science behind limb loading. The findings do, however, demonstrate the need for further laboratory-based investigation into the fundamental effects of load placement on the limbs as well as the need to continue to characterize the practical effects of fielded systems which load in the limbs.

The low statistical power of the data for some variables indicates a need for additional testing to be done with a larger sample population size in order. Since the no armor condition was found to be significantly different in both kinematics and metabolic costs, such a continuation of this study would not need to include the no armor condition, allowing for expedient collection of data for the other two conditions.

This study has indicated that there are no significant effects of load placement on metabolic cost of distal limb loading when loads of 0.75 kg are applied to each shank and loads of 0.5 kg are applied to the forearms. Previous work, though, has found large significant differences in metabolic cost per kilogram with masses of 4 kg applied to either the hands or the feet (Soule & Goldman, 1969; Miller & Stamford, 1987; Legg & Mahanty, 1986). Taking this work a step farther by specifically defining the mass/position relationships in limb loading that elicit increases in metabolic cost increases beyond the effect of the mass alone would be of great interest to both the military and clinicians. With ever advancing technologies and the development of new equipment, space, weight, and capabilities to give and place equipment on the soldier are important issues from the battlefield to the research labs. A detailed definition of the masses and positions on the limbs which induce metabolic costs to increase greatly would have an impact on more than just the level of coverage, weight, and ballistic protection extremity armor designers choose for new systems. If designers of military equipment knew they could

attach a new instrument on the thigh or shank with no negative impact as compared to mounting it on the torso, that designer may decide it is better to place it on the extremity than adding it to the clutter of armor, ammunition, grenades and radios already on the chest and back. In the clinical arena, the design of prosthetics, orthotics, and exercise equipment could benefit from knowing the tipping point at which a mass on the limb begins to effect metabolic cost more greatly due to its location.

This study investigated the effects of extremity armor systems exclusively on bipedal locomotion. Gait was chosen for this study due to its ubiquity among warfighters regardless of environment, and because it is a task that has been thoroughly studied by past and present researchers. The study of bipedal locomotion also lends itself to a study of a sample population such as this one, as it is relatively uniform between individuals, compared to other soldier tasks which may be accomplished very differently between individuals. This is not to say that either armor systems or extremity loading could not notably deteriorate a soldier's performance of other battlefield relevant tasks, such as marksmanship, jumping, crawling, grenade throwing, or vaulting a wall. To the contrary, effects on these tasks should also be investigated in order to better characterize the relationship between such military equipment and physical performance.

Even though the effect of the two levels of extremity armor on the metabolic cost of locomotion were not found to be different (**Figure 8**), further research should be done in how the partial extremity armor configuration differs from the full armor configuration in reducing maximal performance test scores such as timed obstacle course, rush maneuvers, and box lifts (Hasselquist et al., 2008a). With this additional information, a commander on the battlefield would be better suited to decide whether the penalties of a particular extremity armor configuration on metabolic cost and physical performance are worth the ballistic protection coverage of that configuration.

While the current study focused on the effects of extremity armor on metabolic cost and kinematics, much more can be learned in the laboratory setting before making

recommendations to manufacturers on the designer of extremity armor or giving guidance to military commanders on the fielding of extremity armor. Within gait analysis, more work can be done with the current data set to investigate the potential for orthopedic injuries with use of extremity armor. This could be done by analyzing the kinetic data that was collected during the trials in order to examine whether injury inducing changes occur in forces applied to the bones and joints during running and walking with extremity armor, as was found by Hasselquist et al. (2008a).

Another measure that would be of use is electromyography (EMG). Using EMG to sample the electrical activity in the muscles hypothesized to be affected by the extremity armor systems, the changes in muscle activation caused by the loading of the extremity armor can be identified. From these changes, the contribution of those muscle groups to the changes in metabolic cost in walking and running can be determined. Once these causes of increased muscle activity are defined, efforts could be made to mitigate these changes in the design of future extremity armor systems.

As mentioned previously, the data presented here would have been more powerful if additional conditions of torso-borne loads equally the masses of the partial and the full extremity armor configurations had also been evaluated. This would have allowed for more in depth characterization of the effects of the positioning of the armor components on the extremities, independent of the total masses. Similarly, a condition in which subjects wore only the IBA vest, which accounted for the majority of the mass in both the partial and full extremity armor configurations, would have been of great interest to delineate the effects of the large torso load from the extremity armor. Such a condition was included in the previous extremity armor work of Hasselquist et al. (2008a,b), but these researchers did not use a vest loaded to mimic battlefield conditions. These additional conditions of interest could not included in the current study, as the data used for this study was collected as part of another study which limited collection, rather than independent data collection in which all desired conditions could be tested. Future studies

of extremity loading should, when possible, incorporate conditions of torso loads equivalent to those extremity loads tested.

The conditions of this study also did not allow for the investigation of the effects of the distal limb loads, i.e. the shank and forearm components of the IDAS, independent of the effects of the proximal armor components on the thighs and upper arms. It is possible that the proximal limb loading, or some other design characteristic of these components, may have inhibited or hidden effects of the distal armor component. Future research into the effects of extremity armor application to the distal limb segments independently from proximal limb armor may provide new insight into why significant effects were not seen in this study due to the armor components on the distal limbs segments.

CHAPTER 8: CONCLUSIONS

The results of this study demonstrated that there is no physiological gain during locomotion from reducing extremity armor coverage from the full IDAS configuration to a partial extremity coverage configuration of the IDAS with the removal of the distal limb armor segments. The increase in metabolic cost due to extremity armor was unchanged whether the full or partial configuration was worn. The increase in metabolic cost with use of extremity armor was attributed to the added mass of the extremity armor being carried, as no effect of the distribution of the armor's mass was found when metabolic cost was normalized to total mass. This was contrary to the hypothesis that the additional 2 kg weight of extremity armor would yield significantly higher metabolic cost due to the distal placement of the mass on the limbs. The mass of the distal components of the extremity armor that cover the shanks and lower arms may have been too small to produce statistically significant differences in the sample population tested. There were trends observed in gait kinematics that resulted from the mass and distribution of the extremity armor which did not match the changes in joint kinematics expected with carriage of a torso load. This warrants further investigation into the interaction effects of torso loading and extremity loading. Similarly, investigation into the interaction of distal limb loading and proximal limb loading should be further researched.

Based on the results of this study, of the armor types used in this study, the full IDAS configuration provides the best protection while minimizing the exertion required to carry the load as compared to the partial IDAS armor configurations. For future armor designers, this study implies that well balanced extremity armor components of up to 0.75 kg per shank and 0.5 kg per forearm may be acceptable as those masses borne on the limb segments did not significantly increase metabolic cost over that of using torso and proximal limb armor in this study. Further work, though, must still be done to evaluate whether the lack of differences

between the partial and full extremity armor configurations translated to physical performance measures outside of locomotion.

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APPENDIX A

Table A1. Oxygen consumption during walking and running with and without extremity armor.

Oxygen Consumption			
		Mean(L/min)	(SD)
Walking	No Armor	1.21	(0.191)
	Partial Armor	1.48	(0.290)
	Full Armor	1.54	(0.230)
Running	No Armor	2.88	(0.389)
	Partial Armor	3.59	(0.329)
	Full Armor	3.66	(0.419)

Table A2. Oxygen consumption scaled to body mass during walking and running with and without extremity armor.

Oxygen Consumption Scaled to Body Mass			
		Mean (mL/kg/min)	(SD)
Walking	No Armor	14.35	(1.53)
	Partial Armor	17.05	(2.00)
	Full Armor	17.71	(1.23)
Running	No Armor	34.98	(3.21)
	Partial Armor	43.08	(2.42)
	Full Armor	43.88	(4.45)

Table A3. Oxygen consumption scaled to total mass (body mass + armor mass) during walking and running with and without extremity armor.

Oxygen Consumption Scaled to Total Mass			
		Mean (mL/kg/min)	(SD)
Walking	No Armor	13.13	(1.09)
	Partial Armor	12.78	(1.71)
	Full Armor	13.05	(1.08)
Running	No Armor	32.78	(3.12)
	Partial Armor	32.25	(1.67)
	Full Armor	32.35	(2.95)

Table A4. Joint kinematics (range of motion data) for walking and running with and without extremity armor. Means are displayed in degrees, calculated from the maximum flexion and extension angles per volunteer per trial.

	Mean (SD)	ROM Lean	ROM Ankle	ROM HIP	ROM Knee
Walking	No Armor	3.59 (0.81)	27.97 (3.39)	38.00 (2.57)	62.78 (3.37)
	Partial Armor	4.72 (1.54)	23.37 (2.81)	40.68 (2.25)	72.74 (5.04)
	Full Armor	4.02 (0.93)	24.70 (2.32)	38.98 (2.76)	71.58 (2.95)
Running	No Armor	6.64 (1.50)	34.99 (5.48)	43.25 (3.65)	74.76 (8.51)
	Partial Armor	9.08 (1.85)	32.50 (5.11)	46.10 (4.38)	74.27 (8.29)
	Full Armor	8.04 (2.35)	34.01 (5.17)	44.66 (4.26)	75.22 (5.80)

Table A5. ANOVA results and observed power metabolic cost normalized to total mass.

Metabolic Cost Scaled to Total Mass		
	Significance (p<0.05)	Observed Power (0.80)
Walking	0.673025931	0.106919177
Running	0.890879154	0.064511218

Table A6. ANOVA results and observed power for temporal kinematic variables during walking.

Measure	Significance (p<0.05)	Observed Power (0.80)
Cycle Time	0.6996	0.1019
Double Support Time	0.0005	0.9786
Stance Time	0.0968	0.4654
Step Length	0.3049	0.2464
Step Time	0.7107	0.0995
Steps Per Minute	0.7191	0.0976
Strides Per Minute	0.6967	0.1026
Swing Time	0.1899	0.3366
Stride Length	0.2947	0.2528
Stride Width	0.7770	0.0858

Table A7. ANOVA results and observed power for temporal kinematic variables during running.

Measure	Significance (p<0.05)	Observed Power (0.80)
Cycle Time	0.0819	0.4950
Stance Time	0.9869	0.0517
Step Length	0.4916	0.1582
Step Time	0.0865	0.4848
Steps Per Minute	0.1052	0.4479
Strides Per Minute	0.0968	0.4637
Swing Time	0.0672	0.8470
Stride Length	0.4940	0.1574
Stride Width	0.4156	0.1874

Table A8. ANOVA results and observed power for joint kinematic variables during walking.

Measure	Significance (p<0.05)	Observed Power (0.80)
Lean ROM	0.0018	0.9356
Ankle ROM	0.0012	0.9530
Hip ROM	0.0059	0.8591
Knee ROM	0.0000	1.0000

Table A9. ANOVA results and observed power for joint kinematic variables during running.

Measure	Significance (p<0.05)	Observed Power (0.80)
Lean ROM	0.0098	0.8152
Ankle ROM	0.2704	0.2043
Hip ROM	0.0548	0.5681
Knee ROM	0.8707	0.0688

Table A10. ANOVA results and observed power for joint kinematic variables during walking. Only partial extremity armor and full extremity armor included.

Measure	Significance (p<0.05)	Observed Power (0.80)
Lean ROM	0.02776	0.627368
Ankle ROM	0.113403	0.349753
Hip ROM	0.076917	0.42805
Knee ROM	0.36339	0.141544

Table A11. ANOVA results and observed power for joint kinematic variables during running. Only partial extremity armor and full extremity armor included.

Measure	Significance (p<0.05)	Observed Power (0.80)
Lean ROM	0.196437	0.241666
Ankle ROM	0.276673	0.181885
Hip ROM	0.268152	0.187057
Knee ROM	0.515004	0.094452

Events Comprising Physical Activity Data Collection Sessions

Activity		Measures Recorded		Configuration Details
Preparatory activities (including nude body mass and stature measures, marker placement, donning clothing, standing calibration, marker location documentation)				
Range of motion measurement (trunk flexion; arm/leg abduction, adduction, extension, flexion), 3 repetitions		Kinematics		
Rifle aiming in standing (unsupported) position, 3 repetitions		Kinematics		
Rifle aiming in kneeling (unsupported) position, 3 repetitions		Kinematics		
Grenade throwing, 3 throws		Kinematics Kinetics		
10-min Rest Break				
Pre-walk metabolics		Metabolics		
Treadmill walking for 10 min, 1.34 m/s, 0% grade, 1 time		Kinematics Metabolics Kinetics		M4 in low ready position
Treadmill walking for 4 min, 1.34 m/s, 0% grade, 1 time		Kinematics Kinetics		M4 in high ready position
Treadmill walking for 4 min, 1.34 m/s, 18% grade, 1 time		Kinematics Kinetics		M4 in high ready position
Treadmill walking for 4 min, 1.34 m/s, -18% grade, 1 time		Kinematics Kinetics		M4 in high ready position
10-min Rest Break				
Pre-run metabolics		Metabolics		
Treadmill running for 10 min, 2.46 m/s, 0% grade, 1 time		Kinematics Metabolics Kinetics		M4 in low ready position
10-min Rest Break				
Lifting 22.7-kg box from floor level to 1.5 m and returning to floor level, 3 cycles		Kinematics Kinetics		
Lifting 22.7-kg box from floor to surface 1.5 m above floor, 3 cycles		Kinematics Kinetics		
Treadmill walking for 4 min, 1.34 m/s, 0% grade, 1 time		Kinematics Kinetics		M4 in low ready position, MOLLE backpack carried
Ascending and descending 5 stairs, 3 repetitions		Kinematics		M4 in high ready position
Moving from a standing to a prone position and returning to a standing position, 3 repetitions		Kinematics		M4 used as aid to movement
Executing a high crawl for a distance of 4 m, 3 repetitions		Kinematics		M4 cradled in the arms
Session completion activities				

Figure A1. List of events, loads, and collection methods for data collection sessions. Note that not all data collected in these sessions were used in this study.

APPENDIX B

CONSENT TO PARTICIPATE IN RESEARCH

Volunteers under the provisions of AR 70-25 are authorized all necessary medical care for injury or disease which is the proximate result of their participation in such studies.

I,____, having full capacity to consent and having attained my ___ birthday, do hereby volunteer to participate in Acquisition of Physiological and Biomechanical Data on Soldiers to Support Development of a Physics-Based Soldier Modeling and Simulation Tool under the direction of Carolyn K. Bensel, Ph.D. conducted at Buildings 3 and 45, U.S. Army Soldier Systems Center, Natick MA 01760-5020. The implications of my voluntary participation; duration and purpose of the research study; the methods and means by which it is to be conducted; and the inconveniences and hazards that may reasonably be expected have been explained to me by Carolyn K. Bensel, Ph.D. I have been given an opportunity to ask questions concerning this investigational study. Any such questions were answered to my full and complete satisfaction. Should any further questions arise concerning my rights or study-related injury, I may contact: **Human Protections Administrator at the U.S. Army Soldier Systems Center, Building 2, Natick, MA 01760-5020 (ATTN: Ms. Jane Simpson, Commercial Phone: 508.233.5295).**

I understand that I may at any time during the course of the study revoke my consent and withdraw from the study without further penalty or loss of benefits; however I may be requested to undergo certain examinations if, in the opinion of the attending physician, such examinations are necessary for my health and well-being. My refusal to participate will involve no penalty or loss of benefits to which I am otherwise entitled.

PURPOSE OF THE STUDY

This research is being done by personnel at the U.S. Army Natick Soldier RD&R Center to collect measurements of body motions, forces on the body, and energy used as Soldier's do physical activities, such as marching, running, lifting a load, and climbing stairs. The measurements will be made when Soldier's wear a helmet, an armor vest, and extremity armor that covers the upper and lower arms and the upper and lower legs. Measurements will also be made when no helmet or armor is being worn. The measurements will be used to compare how the physical activities are performed with and without the armor. The measurements are also needed for a project to develop software for a computer-based model of a Soldier. The software will be used to design and evaluate body armor. When the software is run, the computerized Soldier will simulate performance of physical activities with and without armor and other military equipment. The software will be used to predict how well a Soldier could perform the activities with the same gear on. Measurements of real Soldiers doing the activities are needed in order to develop software that will make the computerized Soldier move and react like a real Soldier. The software is being developed by scientists and engineers at the University of Iowa.

INCLUSION/EXCLUSION CRITERIA FOR VOLUNTEERS

To take part in this study, you must be within the age range of 18-35 years old, weigh at least 135 pounds, be in good physical health, and pass a medical screening. You should be free of injuries or defects in your bones or joints. You should not have a history of back problems. You should be able to move your shoulders, hips, knees, and ankles freely. You should be able to safely carry loads of up to 108 pounds as you march. If you have highly sensitive skin that is irritated by medical tape, you will not be able to participate. Also, the equipment that will be worn during testing must fit you properly.

During the study, photographs will be taken, videos will be recorded, and laser scan of the body will be taken of those volunteers who agree to be photographed or recorded. The release form to be signed by volunteers who agree to photographing and recording is at the end of this consent form. Agreeing to be photographed or recorded is not a requirement for participation in this study. People can volunteer for and participate in the study without agreeing to have the photos or videos made or the laser scans done.

STUDY PROCEDURES

STUDY TIMES AND LOCATIONS

The study will consist of five sessions. Sessions will be 1 ½ hours to 3 ½ hours long. The total time required for this study will be about 15 ½ hours over the five sessions. All sessions will occur on Monday through Friday between 0700 and 1700 hours (7:00 a.m. and 5:00 p.m.). Some volunteers will be tested in the morning and others will be tested in the afternoon. If any scheduled testing is stopped or postponed due to equipment problems or some other reason, a makeup session will be scheduled. Like the regular sessions, makeup sessions will occur on Monday through Friday between 0700 and 1700 hours (7:00 a.m. and 5:00 p.m.).

The testing for this study will take place here at the U.S. Army Soldier Systems Center. Four of the five sessions will be held in the Center for Military Biomechanics Research, which is in the basement of Building 45. One session will take place in the Anthropometry Lab, which is in Rooms R-310/312 of the Research Building (Building 3).

CLOTHING, EQUIPMENT, AND ARMOR WORN IN STUDY

Three different combinations of clothing, equipment, and armor will be tested in this study. Each study volunteer will test the three combinations, but the order of testing will differ from volunteer to volunteer. In one condition, shorts, socks, and combat boots will be worn. These items total about 4 pounds. In a second condition, shorts, a T-shirt, socks, and combat boots will be worn, along with a helmet, an Interceptor Body Armor (IBA) vest with front and back plates, and extremity armor that covers the upper arms and upper legs. Pouches loaded with grenades and ammunition will be attached to the IBA. The grenades and ammo are dummy items or mockups that have the same shape and weight as the real items. The weight of the gear to be worn for the second condition is about 55 pounds. In a third condition, the items worn in the second condition will be used, plus extremity armor that covers the lower arms and lower legs. The weight of the items for the third condition is about 59 pounds.

An M4 carbine will be carried in the hands while most of the activities are being performed. It is a plastic mockup that weighs about 5 pounds. During one walking activity that lasts 4 minutes, a standard, Army-issue assault pack will be carried on the back. The pack and the load in it will total 44 pounds. Considering clothing, equipment, armor, the carbine and the backpack, the load on the body from the skin out will vary from about 4 pounds to 108 pounds, depending upon the condition being tested and the activity being performed. The heaviest load, the 108-pound load, will be worn for about 4 minutes.

Volunteers are asked to wear their PT uniforms when they report for testing and to bring their combat boots and socks with them. The boots should be broken-in boots that have been used for marching. The investigators will provide the rest of the items needed.

DESCRIPTION OF TESTING

This study will be run until data have been acquired on 12 volunteers. On those days that you are scheduled for a morning test session, you should be sure to eat breakfast before reporting to the test site. Similarly, eat lunch before reporting to the test site for an afternoon session.

If you volunteer to participate in this study, you will attend five study sessions. Four sessions involve performance of the physical activities and one session involves measurement of your body dimensions. The physical activity and the body measurement testing are described here.

Physical Activities

The physical activities that study volunteers will perform are those that we need Soldier data for in order to develop simulations of the activities that the computerized Soldier will do. As you carry out the activities, we will record the way in which you move your body, the forces on your joints and muscles, and the amount of energy you use. Some of the physical activities involve simple movements or simple tasks. These are:

○ **Range of motion.** You will move your arms, legs, or trunk as far as you can in different directions.

○ **Rifle aiming and firing.** Using the plastic M4 carbine, you will assume a standing unsupported position and aim the weapon. You will also aim the weapon after assuming a kneeling unsupported position. You will be aiming at a target mounted on a wall.

○ **Grenade throwing.** Using an overhand throw movement, you will throw a mockup of a grenade toward a target on the floor.

○ **Box lifting and lowering.** You will lift a box that weighs 50 pounds up from the floor to a height of 61 inches (simulating the height of the bed of the Army's newest 5-ton truck) and then lower it to the floor. The box has handles on two sides. Before testing begins, you will be taught the proper way to lift the box and you will practice to make sure that you are doing the task properly.

○ **Box lifting and placing.** You will lift the box that weighs 50 pounds up from the floor using its handles and place the box on a surface that is 61 inches high. Before testing begins, you will be taught the proper way to lift the box and you will practice to make sure that you are doing the task properly.

○ **Ascending and descending stairs.** You will walk up and then down five stairs.

○ **Moving from a standing to a prone position and returning to a standing position.** Beginning in a standing position, you will get down on your stomach. Once you are prone, you will get up and return to a standing position. You will have the plastic M4 carbine to assist you in getting up and down. You will do this task on a padded gym mat.

○ **Executing a high crawl.** You will move from a standing to a prone position and do a high crawl for a distance of about 13 feet. You will have the plastic M4 carbine to carry as you do the high crawl. You will do this task on a padded gym mat.

You will do a task three times in a row and then move on to the next task. After you do a task three times in a row, you will not do that task again that day. You will tell the investigator that you are ready to begin a trial on a task. You will be given a "Go" signal and proceed with the trial. The time it takes you to complete a trial of an activity will not be recorded. We will ask that you do the activity at a normal pace and that you carry out the activity correctly.

The other physical activities to be performed involve walking and running on a treadmill where the speed will be controlled by the investigator. There will be one, 10-minute period of running with the treadmill in a level position at a session. The speed will be set at 5 ½ miles per hour, which is a slow to moderate running speed. There will also be one, 10-minute period of walking with the treadmill in a level position. For walking, the speed will be set at 3 miles per hour, which is a moderate walking speed. There will be four more periods of walking, all at the speed of 3 miles per hour, but these periods will be 4 minutes long. During one of the 4-minute periods, you will walk with the treadmill in the level position. During another 4 minutes, the treadmill will be at an angle of 10 degrees and you will be walking up hill. You will also walk for 4 minutes with the treadmill set so that you are walking down hill at an angle of 10 degrees. During another 4 minutes of walking, the treadmill will be level and you will carry the backpack loaded to a weight of 44 pounds. While walking or running on the treadmill, you will carry the plastic M4 carbine in the low or the high ready position.

Physical Activity Orientation Session (1 session, about 3 ½ hours).

There will be one orientation session before a volunteer begins testing on the physical activities. The orientation session will take place in the Center for Military Biomechanics Research, which is in the basement of Building 45. You will not have a physical activity testing session on the same day that the orientation session takes place. You will report for the session wearing your PT uniform. You will also be asked to bring a pair of broken-in combat boots and socks.

At the beginning of the orientation session, you will try on the clothing and equipment that will be used during the study so that we can find the proper sizes for you. We will then familiarize you with and have you do the physical activities. You will perform the activities first without any armor on and then with the loaded IBA, extremity armor, and helmet. This way, you will gain some experience with the activities and with working in the armor and other gear before the testing sessions begin. As we familiarize you with the physical activities, we will also explain how we will collect measurements during the test sessions of your body motions, the forces on your body, and the energy you use while walking and running. However, during the orientation session, we will not be collecting the measurement data.

You will start the familiarization by walking on the treadmill at 3 miles per hour without any body armor or other equipment. The treadmill will be in a level position. The treadmill speed will be increased gradually and you will be asked to run at 5 ½ miles per hour. Once you are comfortable with the walking and running, which usually takes about 4 minutes at each speed, you will step off the treadmill briefly and the treadmill will be raised to a 10-degree grade. You will walk up the grade at a speed of 3 miles per hour for about 4 minutes. You will step off the treadmill again and the treadmill will be reset. You will then walk down a 10-degree grade for about 4 minutes at a speed of 3 mile per hour. You will step off the treadmill while it is reset to the level position and you will put on the backpack. You will then walk for 4 minutes at a speed of 3 miles per hour with the pack on.

Following a 10-minute break, you will be shown how to do the rest of the physical activities and you will practice doing them. Once you have done all the activities, you will have a 10-minute rest and then you will put on the helmet, the IBA, and the extremity armor. After you get the items on, you will perform all the activities again. That is, you will start with walking and running on the level treadmill and go through the remainder of the activities, with 10-minute rest breaks, just as you did without the armor.

Water will be available throughout the session. Several rest breaks are scheduled. Let the investigator know should you want to take an unscheduled rest break.

Physical Activity Testing Sessions (3 sessions, about 3 ½ hours each).
There will be three sessions during which a volunteer will be tested on the physical activities. All the sessions will take place in the Center for Military Biomechanics Research, in the basement of Building 45. You will have no more than one of these testing sessions on any one day. You will report for the session wearing your PT uniform. You will also need to bring a pair of broken-in combat boots and socks.

You will perform the same activities at each of the three sessions, but you will wear a different one of the three combinations of clothing, equipment, and armor at each session. Table 1 is a listing of the events that will occur at each session. It shows the order of the activities and the measurements that will be recorded for each activity.

At the start of each session, we will give you a pair of spandex shorts to put on and measure your height and weight. You will then put on a chest strap and a wrist band, which is worn on the wrist like a watch. The chest strap contains a device that senses your heart rate and sends information about heart rate to a display on the wrist band. The chest strap does not change your heart rate or how your heart beats. If you are testing armor at the session, you will put that gear on. We will then place reflective markers backed with adhesive tape on your body and the clothing. The markers, which are less than an inch in diameter, are necessary to record

your movements while you do the activities. Specialized cameras are used to make the movement recordings. The cameras record the markers; they do not record your image like regular cameras do. The markers are easily removable at the end of testing.

When the markers are in place, you will stand for about 1 minute and the specialized cameras will record the markers while you are not moving. You will then begin the first activity,

Table 1
Events During Physical Activity Testing Sessions

Activity		Measurements		Notes
Test preparation				Don clothing, equipment, markers put in place, still photos taken
Range of motion, 3 times		Body movements		
Rifle aiming in standing position, 3 times		Body movements		
Rifle aiming in kneeling position, 3 times		Body movements		
Grenade throwing, 3 times		Body movements		
Rest break				
Sit		Oxygen usage, heart rate		
Treadmill walking for 10 min at 3 miles per hour, level surface, 1 time		Oxygen usage, heart rate, body movements, forces		M4 in low ready position
Treadmill walking for 4 min at 3 miles per hour, level surface, 1 time		Body movements, forces		M4 in high ready position
Treadmill walking for 4 min at 3 miles per hour, up hill at 10 degrees, 1 time		Body movements, forces		M4 in high ready position
Treadmill walking for 4 min at 3 miles per hour, down hill at 10 degrees, 1 time		Body movements, forces		M4 in high ready position
Rest break				
Sit		Oxygen usage, heart rate		
Treadmill running for 10 min at 5 ½ miles per hour, level surface, 1 time		Oxygen usage, heart rate, body movements, forces		M4 in low ready position
Rest break				
Lifting and lowering 50-pound box, 3 times		Body movements, forces		
Lifting and placing 50-pound box, 3 times		Body movements, forces		
Treadmill walking for 4 min at 3 miles per hour, level surface, 1 time		Body movements, forces		M4 in low ready position, 44-pound backpack carried
Ascending and descending 3 stairs, 3 times		Body movements		M4 in high ready position
Moving from a standing to a prone position and returning to a standing position, 3 times		Body movements		M4 used as aid to movement
Performing a high crawl for 13 feet, 3 times		Body movements		M4 cradled in arms
Session completion activities				Remove gear, markers

the range of motion movements. Next, you will do rifle aiming and grenade throwing. During these activities, the specialized cameras will be used to record your movements. You will have a 10-minute break after the grenade throwing. Then, you will sit and the oxygen you breathe in with each breath while you are resting will be measured. For this, you wear a nose clip and breathe through a rubber mouthpiece and valve, similar to those found in scuba diving equipment. The mouth piece does not change the air you breathe or how much air you can breathe. You will wear this equipment for about 2 minutes. You will then take off the mouthpiece and nose clip and begin 10 minutes of treadmill walking at 3 miles per hour with the treadmill in a level position.

While you are walking, the specialized cameras will record your walking movements. The treadmill has metal plates that are fixed in place and even with the walking surface. The plates measure the forces you exert on the ground as you walk or run. After you have walked for about 7 minutes, an investigator will assist you in putting on the nose clip and mouth piece while you continue walking, and the oxygen you breathe as you walk will be measured for about 2 minute. At the end of this time, the investigator will assist you in removing the nose clip and mouth piece and the 10-minute walking trial will end. While you are doing this walking trial and whenever you are walking or running on the treadmill, an investigator will observe your heart rate by looking at the display on the wrist band. Testing will be stopped if your heart rate goes too high.

After the 10 minutes of walking, you will step off the treadmill for a short time (2-3 minutes) while we reset the data recording devices. Then you will begin 4 minutes of treadmill walking at 3 miles per hour, with the treadmill set in a level position. During this time, you will carry the plastic M4 in the high ready position. The specialized cameras will record your movements, the metal plates in the treadmill will measures the forces as you walk, and an investigator will observe your heart rate, but your oxygen usage will not be measured. When the 4 minutes are over, you will step off the treadmill again for a short time and the treadmill will be raised to a 10-degree grade. You will walk up hill at 3 miles per hour for 4 minutes with the plastic M4 in the low ready position. After this, there will be another 4-minute period of walking at 3 miles per hour. During this period, you will be walking down hill. The procedure will be the same during each of the 4-minute walking periods. The specialized cameras will record your movements, the metal plates in the treadmill will measures the forces as you walk, and an investigator will observe your heart rate. Your oxygen usage will not be measured during these 4-minute periods.

The period of downhill walking will be followed by a 10-minute rest. Then you will sit for about 2 minutes as the oxygen you breathe in is measured again. The investigator will assist you in putting the nose clip and the rubber mouth piece in place and taking them off. Next, you will begin 10 minutes of running on the treadmill at 5 ½ miles per hour. The treadmill will be in a level position and you will carry the plastic M4 in the low ready position. The procedure on the running trial is the same as the procedure on the 10-minute trial of walking. While you are running, the specialized cameras will record your movements. The plates in the treadmill will measure the forces you exert on the ground and an investigator will observe your heart rate. After you have run for about 7 minutes, an investigator will assist you in putting on the nose clip and mouth piece while you continue to run, and the oxygen you breathe as you run will be measured for about 2 minute. At the end of this time, the investigator will assist you in removing the nose clip and mouth piece and the 10-minute running period will end. This will be followed by another 10-minute rest.

After the break, you will perform the rest of the activities, starting with lifting and lowering and then lifting and placing the 50-pound box while your movements are recorded and the forces are measured. Then you will put on the backpack loaded to 44 pounds and walk on the

treadmill at 3 miles per hour for 4 minutes. The treadmill will be level and you will carry the training M5 in the low ready position. Oxygen usage will not be recorded during this period. You will finish up with ascending and descending five stairs and doing a high crawl. The specialized camera will be used on these activities. At the end of the session, the investigators will remove the markers and assist you in removing any armor or other equipment that you may be wearing.

If you agree to have photos or videos taken by signing the release granting permission to photograph or record your visual image, photographs will be taken when the markers have been put in place, before you begin performing the physical activities. The photos will be used to document the locations of the markers on you. If you sign the release agreement, videos will be taken as you do the activities. The videos will be used to record how your body moves as you carry out the activities.

Body Measurement Session (1 session, about 1 ½ hours).

Measurements of your body will be taken to find out how your measurements compare with those of a large group of Army personnel. This testing will be done in the Research Building (Building 3) Rooms R-310/312. You will report for the session wearing your PT uniform. To take measurements, such as weight, height, and chest circumference, a scale, a measuring tape, and calipers will be used. At the beginning of the session, the investigator will give you spandex shorts to put on. There is a private, secure dressing room where you can change. Then, marks will be made on your skin with an eyebrow pencil. This is to help the investigator make accurate measurements. The marks come off easily with soap and water. You will sit or stand in a semi-related posture (i.e., not at rigid attention) as the measurements are taken.

If you agree to have your visual image recorded by signing the release granting permission, other measurements will be done by making laser scans of your body. Laser scanning is a computerized way of taking a three-dimensional picture of your body surface. (A printout of a scan looks like a very detailed photograph.) The laser and the computer will read and record the combined measurements of your body and whatever you have on.

For the laser scanning, you will stand on a platform with the scanning equipment placed around you and about 3 feet away. The equipment moves up and down in place and does not contact your body. The lasers used in the equipment are the kind used at supermarket check-outs. A scan takes about 20 seconds. You will be scanned while you are wearing shorts. Then you will put on the IBA vest and the extremity armor that covers your upper arms and upper legs and another scan will be done. After you add the extremity armor that covers your lower arms and lower legs, a final scan will be done.

The body measurement session should not be longer than 1 ½ hours. The session may be scheduled on one of the days that you have a session for the physical activity portion of the study or it may be scheduled for a separate day.

POTENTIAL RISKS AND DISCOMFORTS

The whole body scanner presents minimal risk to you. The scanning device uses laser sources that have been rated as Class II lasers and produce low-intensity light, with power like that of a barcode reader used in supermarkets. The laser sources are judged safe for human use. The lasers in the scanner take less than 1 second to pass across each eye during a scan and, therefore, pose a very low injury risk. Further eye safety is achieved by having a volunteer face toward the lasers so that laser radiation is blocked by the water on the surface of the eye and does not penetrate into the eye itself. The laser equipment that will be used in this study

also has safety features that lock off the laser when there is no scan in progress, in the event of a scan failure, and after 30 seconds. In addition, there is an emergency stop button on the equipment. The laser scanner has been used safely in studies at Natick for more than 10 years with no adverse events.

The testing procedures in this study involve wearing armor while you perform physical activities, including walking and running on a treadmill. The procedures also involve carrying a backpack load while you walk on a treadmill. Bearing loads like these on the body is a standard military task that is generally regarded to be of low risk. The foot blister is the most common wound in running and walking. Therefore, you will be asked to wear well-fitting, broken-in boots with properly sized socks. The distances that you will carry a load in this study are relatively short and should involve a lower risk of blisters than longer distances.

Back discomfort commonly results from carrying backpack loads during marches and some muscle soreness sometimes occurs from wearing armor. In this study, the time that you will have a backpack on is very short, approximately 4 minutes. The time that you will be walking or running with armor on is also short; you will not walk or run for longer than 10 minutes at any one time. In addition, you will also set your own pace as you do a number of the physical activities. It is not expected that you will experience muscle soreness from the activities you do in the study. However, you should tell the Principal Investigator if you notice muscle soreness.

There is also a risk of "rucksack paralysis" associated with carrying backpack loads (only 33 cases have been observed over the past several decades). Rucksack paralysis comes about when continuous pressure of pack shoulder straps causes nerve damage, resulting in numbness, pain, and, in extreme cases, paralysis of muscles that stabilize the shoulder. The effects are usually temporary, but some cases have been long-term. In this study, you will be carrying a backpack for no more than approximately 4 minutes at a time and you will be given regularly scheduled rest breaks throughout each study session. You should notify the Principal Investigator immediately of any sensation of numbness and shift the position of the pack straps from time to time. The relatively short periods of load carriage and the regularly scheduled rest breaks you will get in this study should minimize the likelihood of rucksack paralysis.

Stress fractures, or breaks of bones in the foot and leg, have been associated with road marching while carrying loads, especially among recruits undergoing initial military training. Soldiers at higher risk include those with previously sedentary lifestyles, females, older individuals, and, possibly, those carrying excess body weight. In addition, load carriage is sometimes associated with pain of the foot and/or knee. Injuries appear to increase with the distance marched. The fact that you are physically fit and 35 years of age or younger should minimize the risk of stress fracture, foot pain, and knee pain. In addition, the time that you will carry a load is relatively short, which again should minimize the risk of stress fracture or foot or knee pain. Also, you will not run or walk for longer than 10 minutes at any one time.

As forms of moderate to heavy exercise, carrying loads and running can uncover or worsen hidden heart problems, such as not enough blood flow to the heart muscle and irregular beats. Since you are physically fit and active, 35 years of the age or younger, and will be medically cleared before any testing, you are unlikely to have problems with your heart or circulatory system. During all study sessions, you will get frequent rest breaks and water will be available. While you are walking or running on the treadmill, an investigator will also observe your heart rate and stop the testing should heart rate get too high.

There is a risk of injury due to a slip, trip, or fall as you are walking or running on the treadmill. You should be careful to maintain your balance and stay in the center of the treadmill belt. You will be given practice walking and running on the treadmill. In addition, an investigator will be near the treadmill and there are safety bars on the treadmill you can grasp should you start to loose balance. There is also the risk that you will slip or fall as you walk up and down the stairs. An investigator will be near the stairs to assist you should you start to loose your balance.

Reflective markers will be placed on your skin using tape. There may be an unusual skin reaction from the tape. Individuals who have had prior adverse reactions to pastes or adhesives will not be studied. Any electrical equipment to be used in the study will be tested prior to use in the study by a trained individual to ensure its safety.

If any dizziness and/or discomfort occur, testing will be stopped and the medical staff of the USARIEM Office of Medical Support and Oversight will be notified. Water will be offered to you before, during, and after the experiment. You may terminate participation in the study at any time for any reason without penalty.

Prior to participation in the study, all volunteers will undergo medical screening by medical staff personnel, to include clinical review of the medical records, with an emphasis on the musculoskeletal system.

A medical staff member will be on call at all times during the study. The CPR-certified investigator will be alert to signs of medical problems. The investigators will value your health and safety above the importance of data collection. If you develop symptoms of any medical problem, testing will be stopped immediately and the medical staff notified. You will be instructed to notify the researcher of any injury. You will not be expected to do testing that would unduly increase the risk of injury or worsen an existing injury.

The Principal Investigator will immediately report any serious and unexpected events to the medical staff in the USARIEM Office of Medical Support and Oversight. Directions will be displayed clearly next to the phone in the laboratory. A medical staff member, upon notification, will report to the testing site and make an evaluation of the occurrence and determine level of severity, need for further medical treatment, and whether testing should be suspended.

ANTICIPATED BENEFITS TO VOLUNTEERS

This study is not being done to improve your condition or health. You have the right to refuse to participate in this study. You will receive no direct benefits from your partaking in the study. Funds appropriated to the Department of Defense may not be used for research involving a human being as an experimental subject unless: (1) the informed consent of the subject is obtained in advance; or (2) in the case of research intended to be beneficial to the subject, the informed consent may be obtained from a legal representative of the subject. You will receive a copy of this consent form after it has been completed and signed.

MEDICAL CARE FOR RESEARCH RELATED INJURY

Should you be injured as a direct result of participating in this research project, you will be provided medical care, at no cost to you, for that injury. You will not receive any injury compensation, only medical care. You should also understand that this is not a waiver or

release of your legal rights. You should discuss this issue thoroughly with the Principal Investigator before you enroll in this study.

CONFIDENTIALITY

Each study volunteer will be assigned a unique ID number. The ID will not contain any personal identifiers, such a name, social security number, address, date of birth, zip code, etc., and only this study volunteer ID number will be used on all data collection instruments, to include data collection forms, computer records, etc. There will not be any list linking your name to your ID.

Photographs, videos, and laser scans of thebody will be made during testing if a volunteer agrees by signing the release form granting permissions for this. Photographs will be treated so that the person in the photo cannot be recognized. This will be done by investigators on the study before a photograph is seen by anyone who is not working on the study. The investigators will draw a black band across the face in the photo so that the eyes and at least part of the nose cannot be seen. If a volunteer agrees to be videotaped during testing, they will be given a pair of wide-lens, dark glasses that cover the eyes. The glasses will be worn while taping is underway so that the person cannot be recognized on the recording. If the volunteer agrees to have the laser body scans done, the scanned image will be treated so that the person in the scan cannot be recognized. This will be done by the investigators on the study before the scan is seen by anyone who is not working on the study. The investigators will smooth the face on the scan so that the face is not recognizable.

When the results of the research are published or discussed in conferences, no information will be included that would reveal your identity. If photographs or videos of you will be used for educational purposes, your identity will be protected or disguised.

It should be noted that authorized representatives of the U.S. Army Medical Research and Materiel Command are eligible to review research records of individual volunteers as a part of their responsibility to protect human volunteers in research. As a result, they may see your name; but they are bound by rules of confidentiality not to reveal your identity to others. All data and medical information obtained about you, as an individual, will be considered privileged and held in confidence; you will not be identified in any presentation of the results. Complete confidentiality cannot be promised to you, particularly if you are military personnel, because information bearing on your health may be required to be reported to appropriate medical or command authorities.

STUDY DATA THAT WILL BE SHARED WITH THE UNIVERSITY OF IOWA

One of the purposes of taking measurements of study volunteers performing physical activities is to use the data to develop simulation software. When the software is finished, a computerized Soldier will simulate performance of the same activities. Measurements of real Soldiers doing the activities are needed for development of the software. The software is being developed by scientists and engineers at the University of Iowa. They are doing this work under a contract with Natick Soldier RD&EC.

The data of the volunteers in this study will be supplied to scientists and engineers at the University of Iowa. The data will have a volunteer's study ID number on it, but there will be no personal identifiers (e.g., name, social security number) to link the ID number to the volunteer. The data that the University of Iowa will receive are numeric data from: 1) the specialized cameras that record the markers on the body during movements; 2) the force plates that record

forces during walking and running on the treadmill; and 3) the system that measures oxygen during breathing.

For those volunteers that agree to be photographed, videotaped, and scanned during testing, the photographs, videotapes, and scans will be supplied to scientists and engineers at the University of Iowa. The photographs, tapes, and scans will be identified with the volunteer's study ID number, but again there will be no personal identifiers to link the ID number to the volunteer. Before the photographs are released to University personnel, or to anyone who is not an investigator on the study, the investigators will black out the eyes and at least a portion of the nose so that the person in the photo is not recognizable. The videotapes will also be identified with the volunteer's study ID number. Wide, dark glasses will be worn by volunteers when taping is being done so that the person being taped is not recognizable. For the scans, investigators will smooth out the face so that it is not recognizable.

University of Iowa personnel will not have any contact or interaction with study volunteers. They will not be investigators on the study. They will not be involved in the testing or in volunteer briefings.

NEW FINDINGS

During the course of the study, you will be informed of any significant new findings (either good or bad), such as changes in the risks or benefits resulting from participation in the research or new alternatives to participation, that might cause you to change your mind about continuing in the study. If new information is provided to you, your consent to continue participating in this study will be re-obtained.

IDENTIFICATION OF INVESTIGATORS

In the event of a research related injury or if you experience an adverse reaction, immediately contact the Principal Investigator: Carolyn Bensel, Ph.D. at phone number 508.233.4780 or the USARIEM Office of Medical Support & Oversight at phone number 508.233.4962.

If you have questions regarding your participation and rights as a research volunteer, you may contact Ms. Jane Simpson, NSRDEC Human Protections Administrator at phone number 508.233.5295.

VOLUNTEER WITHDRAWAL

Participation in this research is voluntary. If you choose not to participate, there will be no penalty or loss of benefits to which you are otherwise entitled. If you decide to participate, you are free to withdraw your consent and discontinue participation at any time without penalty or loss of benefits. If you choose not to participate, that will not affect your relationship with the U.S. Army Natick Soldier Systems Center.

WITHDRAWAL BY THE INVESTIGATOR

The investigator may withdraw you from participating in this research if circumstances arise which warrant doing so. If you experience any of the following side effects: dizzy, faint, sore muscles or joints, or if you become ill during the research, you may have to drop out, even if you would like to continue. If you are consistently late or absent from the scheduled sessions you may be asked to discontinue. If you act in a disruptive or unsafe manner and do not follow the researcher's directions, you will be asked to discontinue the study. The investigator will make the decision and let you know if it is not possible for you to continue. The decision may

be made either to protect your health and safety, or because it is part of the research plan that people who develop certain conditions may not continue to participate.

SIGNATURE OF RESEARCH VOLUNTEER

I have read the contents of this consent for and have listened to the verbal explanation given by the investigator. My questions have been answered to my satisfaction. I give consent to take part in this study. Signing this consent document does not give up any of my legal rights nor does it release the investigators, institution, or sponsors from their responsibilities.

____ Date of Briefing________________
Name of Volunteer

____ Date of Signature_______________
Signature of Volunteer

WITNESS TO VOLUNTEER'S SIGNATURE

I attest that, on the date of my signature, the individual signed this consent form in my presence as his or her voluntary act or deed.

____
Name of Witness

____ Date of Signature______________
Signature of Witness

Release Granting Permission to Photograph or Record the Visual Image of an Individual on an Approved Human Research Study

Because you are a participant in the human research study entitled, "Acquisition of Physiological and Biomechanical Data on Soldiers to Support Development of a Physics-Based Soldier Modeling and Simulation Tool" conducted by the U.S. Army Natick Soldier Research, Development and Engineering Center under the direction of Carolyn K. Bensel, Ph.D., we are asking you to give us permission to take photographs or other images of you during the study.

Do not complete this form if you do not want to be photographed or visually recorded.

I hereby **grant** permission to use photographs or other images from the above study in presentations or publications provided I cannot be recognized in the photograph or image.

1. Volunteer		
Typed or printed name (Last, first, middle initial)	Signature	Date (YYYYMMDD)
2. Witness		
Typed or printed name (Last, first, middle initial)	Signature	Date (YYYYMMDD)